Advancing the LCA Ecosystem

A Policy-Focused Roadmap for Reducing Embodied Carbon

REPORT | SEPTEMBER 2023

Carbon Leadership Forum

About the Carbon Leadership Forum

The Carbon Leadership Forum accelerates the transformation of the building sector to radically reduce the greenhouse gas emissions attributed to materials (also known as embodied carbon) used in buildings and infrastructure.

We research, educate, and foster cross-collaboration to bring embodied carbon of buildings and infrastructure down to zero.

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CONTENTS

EXECUTIVE SUMMARY

Introduction and Objectives

Policy action on embodied carbon is growing quickly. Already, 2021–2023 has seen an unprecedented number of introduced and passed policies targeting embodied carbon reductions in the building and infrastructure sectors in the United States, Canada, and internationally. Policies aimed at reducing the embodied carbon of building and infrastructure projects and construction materials typically leverage life-cycle assessment (LCA) as a methodology to measure the impacts of a product or project and compare them against a percentage reduction target or embodied carbon performance standard (i.e., global warming potential (GWP) limit).

The effectiveness of policies in reducing embodied carbon relies on the health of the underlying **LCA ecosystem** – the standards, guidelines, data sources, tools, and actors/organizations that constitute the interdependent building blocks of LCA – to create consistent, reliable estimates of embodied carbon to report and benchmark products and projects.

In this report, the CLF lays out a vision for an ideal LCA ecosystem optimized for use as a tool for policy and private sector decarbonization action (focusing on the United States and Canada). This report aims to address existing obstacles to progress through three objectives:

1. **Demystify the standards, data sources, tools, and actors** that make up the current LCA ecosystem.
2. **Propose a roadmap** to maximize the potential of LCA of products and projects as a tool for effective policy.
3. **Highlight existing initiatives** to reduce redundancy and accelerate action.

Existing standards, data, and tools have enabled the growing action and knowledge on embodied carbon we see today, but the shift from voluntary best practice to incentives and regulations has increased the need for access, consistency, and transparency. For effective policy, federal and state government agencies, policymakers, and national/international nongovernmental organizations (NGOs) need to take on leadership to expand these efforts, create more standardization and coordination across siloed sectors, and ensure equitable representation and participation in standards development and programs.

An "ideal" LCA ecosystem optimized for policy would be:

- **open and transparent** through shifting the balance from proprietary data and models to open, high-quality data in public repositories and investing in open data infrastructure;
- **accessible** through expanded access to training, streamlined processes and tools for reporting, and financial support for those who really need it;
- **more comparable and reliable**, with differences in LCA results reflecting differences in the carbon footprints of products or projects, not differences in the data, tools, and methodologies used by practitioners;
- **globally harmonized** to streamline the use of LCA data and tools across borders and sectors;
- **able to keep pace with new materials, technologies, and processes** to better track and support decarbonization and to fill the gaps in current standards, data, and tools by exploring and measuring those new materials, technologies, and processes.

Exploring the Current LCA Ecosystem

The building blocks of the LCA ecosystem are (1) standards and modeling guidelines, (2) data sources, (3) tools, and (4) actors/organizations. The first section of the report provides an overview of each of the following four critical areas related to embodied carbon reductions in the built environment:

- **Foundational LCA:** foundational building blocks related to all scopes and scales of LCA;
- **Product LCA:** assessments of individual products, product types, and materials;
- **Building LCA:** assessments of buildings or parts of buildings (e.g. bays, wall assemblies, structures), also commonly referred to as whole-building LCA (WBLCA);
- **Roadway LCA:** assessments that include pavements and potentially other roadway infrastructure components such as bridges, tunnels, sidewalks, etc. This report considers the more commonly used term "pavement LCA" (FHWA, 2016) to be a subset of "roadway LCA." Roadway LCA is a subset of the larger category of infrastructure.

Key findings are summarized here by section:

Standards: International, consensus-based standards published by third-party standards organizations exist for foundational LCA, environmental product declarations (EPDs), building LCA, and roadway LCA. However, these standards vary in how much prescriptive or detailed guidance they provide to practitioners and are not globally harmonized. Effective LCA standards need to be both flexible – to be useful across different applications and over time – and prescriptive – to yield consistent methods, assumptions, and results across assessments. These two aspects are often in tension with each other. The less prescriptive a standard is, the more likely that the results of an LCA will vary due to differences in modeling practices, rather than differences associated with building materials or the building project. Product category rules (PCRs) are the most critical standards for guiding the consistent implementation and comparison of EPDs. More prescriptive and effective standards are still needed in the United States for building and roadway LCAs that can be referenced by policy and provide enough detailed guidance to result in comparable and reliable results.

Additionally, there is a need for updates to TRACI 2.1 (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts), a life cycle impact assessment (LCIA) method published by the U.S. Environmental Protection Agency (EPA), and for development of a widely adopted methodology for calculating the benefits of carbon storage and land use and land-use change (LULUC) impacts.

Data Sources: LCAs rely on both primary “foreground” data and secondary “background” data. The terms “foreground” and “background” are relative: one study’s foreground data can become another study’s background data. For example, a cement supplier collects *foreground data* on its cement facility’s operations to generate a cement product EPD. A concrete manufacturer that uses that particular cement product in its concrete mix may use the cement product EPD data as *background data* for the concrete mix EPD. Both the cement manufacturer and the concrete producer would rely on background data on fuels and electricity used at their facilities.

Background data sources that can be used *across* assessment types are critical to creating comparable and reliable results for policy and allowing, for example, EPDs to be used as a data source for building LCA or other product EPDs. Currently, background data sources come from a patchwork of proprietary and public datasets. Federal agencies play a critical role in providing public, transparent background data sources through the Federal LCA Commons and specific agency publications, but the management and updates to these datasets are currently underfunded and understaffed. Federal support in creating transparent, open life cycle inventory (LCI) data sources that can be prescribed by standards will be a critical step to more effective policy.

Foreground data collection is done by a wide variety of actors. Templates for collecting foreground data for products and projects will support consistency and comparability while reducing the time and effort required for project teams.

Tools: Existing tools already support the measurement of the embodied carbon of products, buildings, and pavements. Obtaining more comparable results from tools requires the adoption of national standards and harmonized background data through more up-to-date, comprehensive public background data sources that can be referenced *across* tools. The results from building and pavement/infrastructure LCA tools are not yet collected in a central database for benchmarking or reporting compliance in the United States or Canada.

Actors: A large number of stakeholders make up the LCA ecosystem, including policymakers, government agencies, standards organizations, voluntary programs, rating systems, NGOs and trade associations, academia, LCA practitioners, tool developers, owners / building developers, designers (architects, engineers), contractors, and manufacturers.

A Roadmap: Existing Challenges and Proposed Solutions

When synthesizing the solutions in this document, we found six themes across all areas, summarized in Figure 1: stronger standards, transparent data, increased practice, aligned tools, reporting databases, and better benchmarks. While these can be aligned into sequential steps, this process is iterative. For example, standards are used to produce data and to help align tools and benchmarks, which results in additional knowledge that will be used to improve the standards and further improve future data, tools, and benchmarks.

Each roadmap section of the report includes a summary of existing challenges followed by key steps to address these challenges for each LCA type.

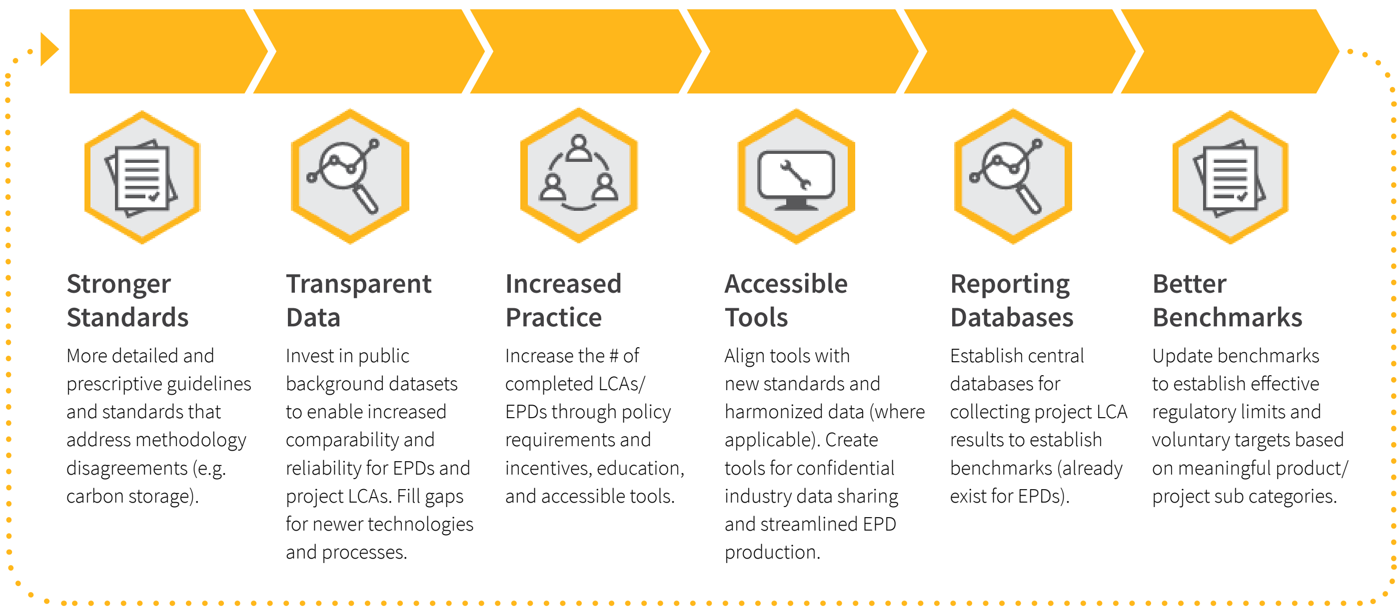

Figure 1. Themes across solutions for advancing the LCA ecosystem The roadmap for each of the four types of LCA addressed in the report differs, but six themes emerge across: stronger stsandards, transparent data, increased practice, accessible tools, reporting databases, and better benchmarks. These steps are sequential, the process is also iterative. For example, standards are used to produce data and help align tools and benchmarks; then we learn and go back and improve the standards which improves future data and tools and benchmarks.

Foundational LCA Ecosystem

Key challenges identified in the Foundational LCA section are the need for more reliable, transparent, and comparable LCA results, more access to LCA concepts, data, and tools, and more LCA education and training. Solutions laid out in this report for addressing these challenges are:

1. Increase access to high-quality, up-to-date, public LCA datasets and models as consistent sources for background data by improving staffing, funding, and planning for sustained updates to U.S. and Canadian federal LCI databases and public datasets.

2. Improve LCA standards to provide more detail and consistency by updating international standards to be more prescriptive on LCI data and LCA modeling protocols, updating the TRACI LCIA method, and developing a consensus standard for evaluating the GWP benefits of carbon storage.

3. Provide more LCA training and credential opportunities through university LCA programs to increase the number of LCA practitioners and support LCA community and practitioner consistency.

4. Fill gaps in available background data to increase the accuracy of LCA results by providing user-friendly tools for industry to report LCA data and LCA models confidentially to create more technology- and region-specific LCI data, filling gaps in public LCI repositories in relation to alternative materials and technologies, and strengthening service life and end-of-life (EOL) scenario data.

5. Improve the interoperability between LCI datasets and LCA datasets and tools through supporting international efforts to adopt a central nomenclature for elementary flows, increase LCI-LCIA interoperability, and move between datasets.

6. Explore opportunities to use LCA to address policy priorities beyond carbon through research and consensus-building on which impact factors outside of carbon are policy ready for addressing land, water, air, and environmental justice priorities.

Product LCA and EPDs Data Ecosystem

Key challenges identified in the Product LCA and EPDs section are the need for more access to EPDs and EPD data, current limitations on PCR development, inconsistency between North American and international EPD requirements, and the scarcity of representative, production-weighted data for establishing emissions thresholds. Solutions detailed in this report are:

1. Continue to increase EPD availability and accessibility by requiring EPDs in policy, providing government-funded assistance for EPD production and verification, increasing access to EPD generators, providing more widespread training, and adopting digital formats.

2. Strengthen EPD standards (PCRs) and PCR development processes to increase EPD reliability and comparability through supporting program operator funding and collaboration, diversifying stakeholder engagement on PCR committees, strengthening verification processes, and improving individual PCRs to be more detailed and prescriptive (background data prescriptions, standardized specificity requirements and definitions, uncertainty reporting, etc.).

3. Create or adopt national and/or international PCR harmonization requirements to support the use of EPDs as data sources for project or other product LCAs through voluntary adoption of requirements across program operators (e.g. UN Industrial Deep Decarbonization Initiative (IDDI), ACLCA Open PCR standard) or mandatory PCR harmonization requirements (federal standard, conformity assessment program, or similar).

4. Increase access to public EPD generator tools that allow for two-way integration with public datasets, are aligned with updated PCRs, and provide streamlined EPD development through simple data collection templates for manufacturers.

5. Increase the availability of industry data for setting policy emissions thresholds by requiring representativeness and statistical data measures in industry-wide EPDs (IW-EPDs), increasing participation in IW-EPD development, and leveraging industry input to determine appropriate product and region subcategories for emissions thresholds.

Building LCA Ecosystem

Key challenges identified in the Building LCA section are (1) the need for more reliable and consistent building LCA results, (2) the lack of building LCA benchmarks and targets, and (3) policy challenges. Solutions detailed in this report for addressing these challenges are:

1. Create or adopt a national/North American building LCA standard with prescriptive practitioner guidance for calculations and reporting, covering scope, modeling methods and assumptions, data requirements, uncertainty, and a common reporting framework.

2. Fill gaps in data availability for materials and construction processes through more guidance and training on primary data collection, filling gaps in available LCI data for new or otherwise missing products, providing geography- and/or technology-specific generic LCI data, improving EPDs' viability as data sources, and improving service life and EOL scenarios.

3. Increase access to consistent and comparable building LCA tools through working with tool developers to update tools to a national or North American building LCA standard and leveraging harmonized background datasets when possible.

4. Increase building LCA use, accessibility, and trust through requiring or incentivizing building LCA disclosure in codes and policies, providing practitioner training, providing general education for nonpractitioners, and building confidence in results through verification.

5. Collect building LCA results and material quantities in a central database that aligns with the reporting framework outlined by a North American building LCA standard, and connects to existing repositories and tools.

6. Set effective and appropriate regulatory limits and voluntary targets for policy by calculating national and/or regional baselines for limits and Paris-aligned building carbon budgets to inform voluntary targets and incentive programs.

7. Identify prescriptive building embodied carbon reduction strategies and pathways to complement GWP thresholds for use by policies and green building certifications that are updated over time as practices evolve and new materials/approaches become mainstream.

Infrastructure LCA Ecosystem

Infrastructure is a broad sector with many unique project types. Roadways are identified as the primary area for current focus related to LCA of infrastructure, with opportunity to expand to other types in the future. Key challenges identified in the roadway LCA section are (1) the need for more reliable and consistent infrastructure LCA results, (2) the limited scope of assessments and tools available, particularly beyond pavement, and (3) the lack of roadway LCA benchmarks and targets. Solutions detailed in this report for addressing these challenges are:

1. **Increase the number of roadway LCAs completed** through adjusting policy to require disclosure of LCA results for certain roadway projects, providing LCA training for transportation agency employees, and providing general education for others.

2. **Create North American infrastructure LCA standards**, beginning with pavement LCA, that prescribe scope, key background data, methods, reporting metrics, and LCIA method. Provide guidance for inventorying. Build on pavement LCAs to expand to roadways and other infrastructure.

3. **Build up public background datasets and fill gaps in data availability** through more guidance on training on primary data collection, filling gaps in available LCI data, providing geography- and/or technology-specific generic LCI data, and improving EPDs' viability as data sources.

4. **Increase access to infrastructure LCA tools** through updating existing pavement tools to align with the national standard, creating new LCA-CAD (computer-aided design) integrated tools, providing digital infrastructure for transportation agencies, and creating new tools beyond pavement.

5. **Collect roadway LCA results and material quantities in a central database** for analysis and benchmarking. Potentially leverage current tool providers or academic institutions to support transportation agencies.

6. **Set regulatory limits and voluntary benchmarks** by calculating national and/or regional baselines as well as Paris-aligned project carbon budgets to inform voluntary targets and incentive programs.

7. **Provide evidence-based prescriptive strategies as complementary pathways** to performance limits in policies and voluntary programs.

1. INTRODUCTION

Embodied carbon[1] refers to the greenhouse gases (GHGs) emitted during the manufacturing, transportation, installation, maintenance, replacement, and disposal of construction materials used in buildings, roads, and other infrastructure. The production of cement, iron, and steel – major materials used in construction – accounts for nearly 18% of total global GHG emissions (Hasanbeigi et al., 2021). In order to avoid the most catastrophic impacts of climate change, it is essential that we reduce embodied carbon now, and develop a pathway to low-carbon construction on every building project. Policy is an essential step toward creating the scale of action required to rapidly reduce embodied carbon in construction.

Policy action on embodied carbon is growing quickly. Already, 2021–2023 has seen an unprecedented number of introduced and passed policies targeting embodied carbon emissions reductions in the building and infrastructure sectors in the United States, Canada, and internationally.[2] Policies aimed at reducing the embodied carbon of building projects and construction materials leverage LCA as a methodology to measure the results of a product or project and compare them against a percentage reduction target or emissions threshold.[3]

LCA is an analysis methodology that estimates the environmental impacts of a building, product, or process over its full life cycle, from raw material extraction through EOL and disposal. LCA models do this by mapping all of the inputs and outputs of materials and energy through a system over time and consistently reporting resultant environmental impacts. One impact that LCA models calculate is the total contribution to climate change. This impact is reported as GWP, referred to in short as "embodied carbon."

The effectiveness of policies in reducing embodied carbon relies on the health of the underlying **LCA ecosystem** – the standards and guidelines, data sources, tools, and actors/organizations that constitute the interdependent building blocks of LCA – to create consistent, reliable estimates of embodied carbon to measure and benchmark products and projects.

Heightened interest in LCA as a tool for policy has resulted in a unique opportunity to focus new resources and time on advancing the LCA ecosystem to enable more widespread, impactful policy action.

Whether or not the LCA ecosystem will be used by industrial and building policies is no longer a question but a given. What is in doubt is whether stakeholders across the construction industry can come together quickly enough to take advantage of this opportunity to optimize LCA infrastructure as a more effective tool for decarbonization.

Vision and Objectives

By providing a standardized and robust approach to estimating the carbon impacts of construction products and projects, LCA can support more informed decision-making from early design through procurement. This report outlines a vision for an ideal LCA ecosystem optimized for use as a tool for policy and private sector decarbonization action. These improvements can happen **parallel** to ongoing policy and private sector action.

Existing standards, data, and tools have enabled the growing action and knowledge on embodied carbon we see today,

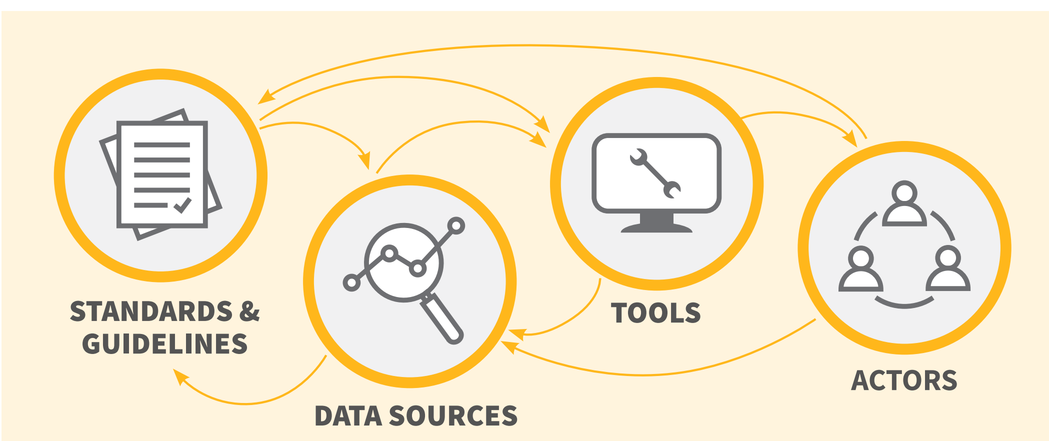

Figure 2. The LCA ecosystem. Standards and guidelines, data sources, tools, and actors constitute the interdependent building blocks of LCA and LCA results, including GWP (embodied carbon). The strength of the LCA ecosystem is critical to the effectiveness of policies targeting embodied carbon.

but the shift from voluntary best practice to incentives and regulations has increased the need for access, consistency, and transparency.

Currently, progress is impeded by a lack of communication, coordination, and knowledge. First, there is confusion or misunderstanding about which standards, data sources, and tools do or don't exist and which are the source of current challenges. In particular, the landscape of background datasets and standards in the Foundational LCA sections of this document is often ignored as a potential piece of the solution because it is difficult to understand and LCA practitioners have historically not engaged in policy or private sector decarbonization conversations. Second, sectors are not talking to each other. To date, most action has been bottom-up, led voluntarily by private sector leaders. This has resulted in silos between different industries and sectors as well as redundant or conflicting harmonization efforts. Last, without policy intervention, there simply has not been the same need for top-down standardization of how LCA results are modeled, reported, and collected.

In an effort to address these challenges and accelerate movement toward this ideal ecosystem, this report aims to:

1. **Demystify the standards, data sources, tools, and actors** that make up the current LCA ecosystem.
2. **Propose a roadmap** to maximize the potential of LCA as a tool for effective policy.
3. **Highlight existing initiatives** to reduce redundancy and accelerate action.

This report is focused primarily on the United States and Canada, but European standards and initiatives have been included where they are a helpful point of comparison or reference. Similarly, this report is focused specifically on LCA, and while there are efforts to align LCA with other carbon accounting methods – such as the GHG Protocol's Scopes 1, 2, and 3 framework – these other carbon accounting methods are outside the scope of what is discussed in this report.[4]

Approach

The findings in this report are based on a review of existing reports and literature, expert interviews held January–April 2023, and virtual workshops held in April 2023 to collect input from 44 different organizations across the United States and Canada representing perspectives from architecture, engineering, and construction (AEC) professionals, manufacturing, LCA practitioners, NGOs, and government agencies. See Appendix C for more information.

This report also builds off of the input and research collected and synthesized by our team at CLF in collaboration with Building Transparency, RMI, New Buildings Institute, the American Council for an Energy-Efficient Economy (ACEEE), and Third Way for the request for information EPA-HQ-OPPT-2022-0924 for the U.S. EPA, submitted on May 1, 2023.

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1. The terms "embodied carbon," "embodied carbon emissions," and "embodied emissions" can be used interchangeably.

2. To learn more about existing policies and track action, visit the CLF Policy Toolkit.

3. This report uses the term "emissions threshold" to refer to a static GWP value set by a policy, against which individual results (e.g. from an EPD or WBLCA) are compared. It generally aims to be some particular point in the distribution of the market – e.g., average, median, 20th percentile, 80th percentile, etc. We use the term "threshold" in alignment with Dell (2020). Other authors and reports refer to the same or similar concept with different terms, including "GWP limit" (DGS, 2021), "emission standard" (Tilak et al., 2022), "baseline," "target," and "benchmark."

4. The draft second edition of the RICS Professional Standard *Whole Life Carbon Assessment for the Built Environment* includes Appendix A Relationship of impacts per life cycle stage to the reporting of GHG emissions with the GHG Protocol. https://consultations.rics.org/whole_life_carbon_standard/viewCompoundDoc?docid=13626324&sessionid=&voteid=&partId=13632564

2. EXPLORING THE CURRENT LCA ECOSYSTEM

This section gives an overview of four content-oriented subsets of the **LCA ecosystem** – the standards and guidelines, data sources, tools, and actors/organizations that constitute the interdependent building blocks of LCA and the GWP values used in policy:

1. **Foundational LCA:** foundational building blocks related to all scopes and scales of LCA;
2. **Product LCA:** assessments of individual products, product types, and materials;
3. **Building LCA:** assessments of buildings or parts of buildings (e.g. bays, wall assemblies, structures), also commonly referred to as whole building LCA (WBLCA);
4. **Roadway LCA:** assessments that include pavements and potentially other roadway infrastructure components such as bridges, tunnels, sidewalks, etc. This report considers the more commonly used term "pavement LCA" (FHWA, 2016) to be a subset of "roadway LCA." Roadway LCA is a subset of the larger category of infrastructure.

This section provides a basic understanding and overview of components of the LCA ecosystem to lay the foundation for understanding challenges and opportunities in Section 3.

2.1 Building Blocks of the LCA Ecosystem

Each subset overview includes descriptions of the four building blocks of the ecosystem: standards and guidelines, data sources, tools, and actors/organizations.

1. Standards and guidelines govern and inform the methods and processes of product and project LCA. While all of the resources included here define or interpret the methods and processes of LCA, they are divided here into two types, based on level of authority:

- **Standards** establish mandatory uniform technical criteria, methods, processes, and requirements for LCA. They are typically produced by third-party standards organizations and require the formal consensus of technical experts before publication.

  The International Organization for Standardization (ISO) provides the primary global LCA standards. ISO standards (and similar for the European Standards (EN)) are developed through a multi-stakeholder process, where a technical committee comprising global experts from industry, academia, NGOs, and government uses a consensus-based approach to create the scope and content of the standard. The creation and updating of these standards can happen at any time (i.e., there is no set interval for updates) based on industry need (ISO, 2023).

  An example standard is ISO 14040:2006 (ISO, 2006a), an international standard that describes the principles and framework for LCA.

  Effective LCA standards need to be both flexible – to be useful across different applications and over time – and prescriptive – to yield consistent methods, assumptions, and results across assessments. These two aspects are often in tension with each other. As discussed in the Roadmap section of this report, more prescriptiveness – especially in those standards that are more narrow in focus such as PCRs – can greatly improve their usefulness for policy.

- **Guides/guidance/guidelines** provide recommendations, interpretation of standards, general direction, and advice for the technical criteria, methods, processes, and practices of LCA. Guidelines can be developed by anyone and they do not require the formal consensus of technical experts. Guidelines are typically nonmandatory, but some policies may publish guidance documents that aim to support compliance with mandatory policies.

2. Data sources include both primary "foreground" data and secondary "background" data.[5] For any given LCA study, the data can be categorized as part of either of these two systems:

- **Foreground system:** activities under the operational control of the entit(ies) creating the final product or project, or commissioning the study. Foreground data is **primary data** collected for that particular study.
- **Background system:** everything else – activities outside of the control of the entit(ies) creating the product or project, or commissioning the study. Background data is **secondary data** collected previously by a third party, not for the particular study. Background data may be specific to a certain supplier, industry-average, or generic (see definitions below). Background data typically constitutes the vast majority of the total number of processes included in an LCA (more than 95% according to Wernet et al. (2016)). Given this significance, it is very important to continue to improve the quality, accessibility, and interoperability of

5. In line with how the terms are typically used, this report uses the terms "foreground data" and "primary data" interchangeably, and the same for "background data" and "secondary data" (Feraldi, 2023).

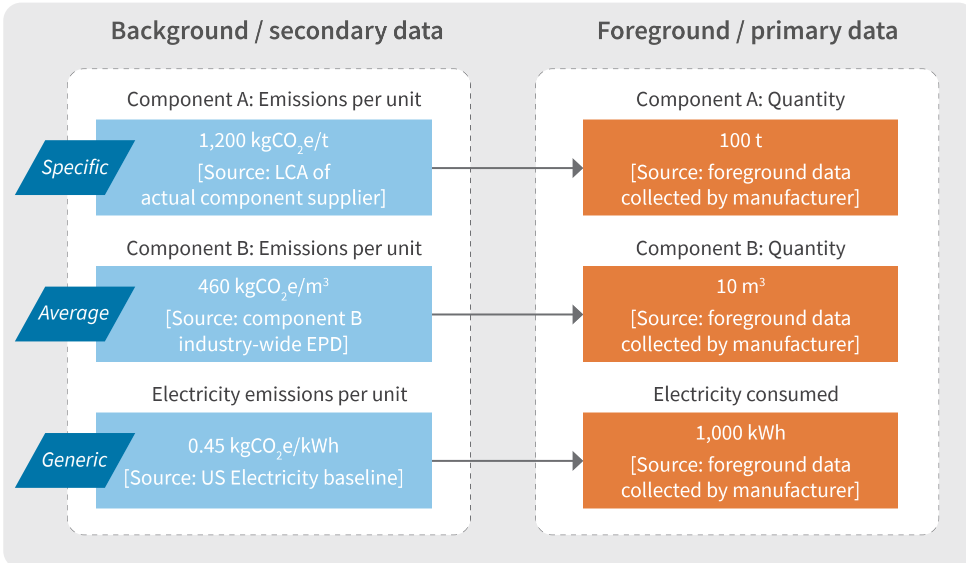

Figure 3. Illustration of background/secondary and foreground/primary data. Foreground data includes activities under the operational control of the entity doing the assessment (e.g., manufacturer producing an EPD). Background data is everything else, and may be specific, average, generic, or proxy (not shown).

background data, as described in various sections of this report.

The terms foreground/primary and background/secondary are relative: one study's foreground data can become another study's background data. For example, a cement supplier collects *foreground data* on its cement facility's operations to generate a cement product EPD. A concrete manufacturer that uses that particular cement product in its concrete mix may use the cement product EPD data as background data for the concrete mix EPD.[6]

In addition to the foreground/background distinction, data can be described according to its specificity.

- **Specific data:** "data representative of a product, product group or construction service, provided by one supplier" (EN 15804:2012+A2:2019). Sometimes this is modified to describe a particular aspect of specificity, such as "facility-specific" (data from one facility, not an average of data from across a manufacturer's multiple facilities).
- **Average data:** "data derived from specific production processes" which has been aggregated (EN 15804:2012+A2:2019).

  Example #1: specific data collected from each of a supplier's multiple facilities that is later aggregated to provide a facility-average dataset for that manufacturer.

  Example #2: specific data collected from multiple manufacturers which is combined to create an industry-average dataset (for, e.g., an industry-average EPD).
- **Generic data:** "data that is not directly collected, measured, or estimated [in either the foreground or the background system], but rather sourced from a third-party life-cycle-inventory database or other source" (European Commission, 2021).

  Example: an EPD uses generic LCI data for combustion of diesel fuel, collected independently of the particular EPD or any upstream suppliers.
- **Proxy data**: "approximate data [from, e.g., a similar product or process] if no system specific data or generic data are available" (ISO 21930:2017, 3.5.5).

3. Tools support the LCA process by, for example, connecting background datasets with user-generated foreground data to model a product or project and provide LCA results. Tools typically allow a user to: (a) define the system and input foreground data, (b) combine the user-generated information with background data to generate the inventory for the system, and (c) connect the resulting inventory with an LCIA method and characterization factors to generate LCIA results.[7]

6. The authors of this report strive to align with international standards and other precedents when defining terms, but there is variation in how these terms are used. Other sources may not use the terms foreground data and primary data synonymously (the same for background data and secondary data). For example, what this report would describe as specific background data (e.g., a cement supplier's facility-specific EPD used to represent that supplier's cement product in a concrete LCA), another source may call primary background data.

7. Some tools combine the inventory and LCIA steps by using background data sources (such as EPDs) that are already in the form of LCIA results.

Tools vary widely by purpose. There are sophisticated LCA modeling tools that are applicable across all types of products and systems (not just construction focused). There are also LCA tools built explicitly to support assessments of construction products and projects, such as EPD generator tools, EPD databases, building LCA tools, and pavement LCA tools.

4. Actors and organizations create and use the standards and guidelines, data, and tools described above. Examples of actors include federal agencies, state transportation agencies, academics, nonprofits, industry trade organizations, program operators, manufacturers, designers, contractors, LCA practitioners, building owners, and software developers.

2.2 Foundational LCA Ecosystem

This section describes the standards, data sources, tools, and actors that relate to LCA broadly and underlie both product- and project-level LCA.

As shown in Figure 4, LCAs are often composed of nested models: each process is itself based on an LCA model, which in turn is likely based on additional LCA models. Practitioners developing a project LCA or an EPD may see these only as data points, but the reliability and comparability of these data points is critical to the reliability and comparability of the overall LCA. This section focuses on the most general and broadly applicable level of LCA that is a foundation for other types.

2.2.1 Foundational LCA Standards and Modeling Guidelines

International standards published by ISO provide standardized principles, methodologies, and reporting requirements for LCA. North America-focused assessments typically follow these ISO standards. LCIA methods are also included here as they are applicable across all types of LCA.

ISO standards for foundational LCA

LCA is a practice that can be applied across many industries and at many scales. The two general standards here provide the overall LCA framework, with intentionally broad aspects that are open to interpretation (U.S. EPA, 2023). More specific standards and guidance documents published by ISO, the European Committee for Standardization (CEN), program operators, and others build upon these general standards to provide rules for specific applications (e.g., EPDs or WBLCA) and are listed in later subsections of this report.

- ***ISO 14040:2006 Environmental management — Life cycle assessment — Principles and framework*** is the foundational standard that describes the principles and framework for LCA (ISO, 2006a), including: goal and scope definition, life cycle inventory (LCI) phase, life cycle impact assessment (LCIA) phase, interpretation, reporting, limitations, and conditions of use. This standard is quite broad in that it applies to all types of products

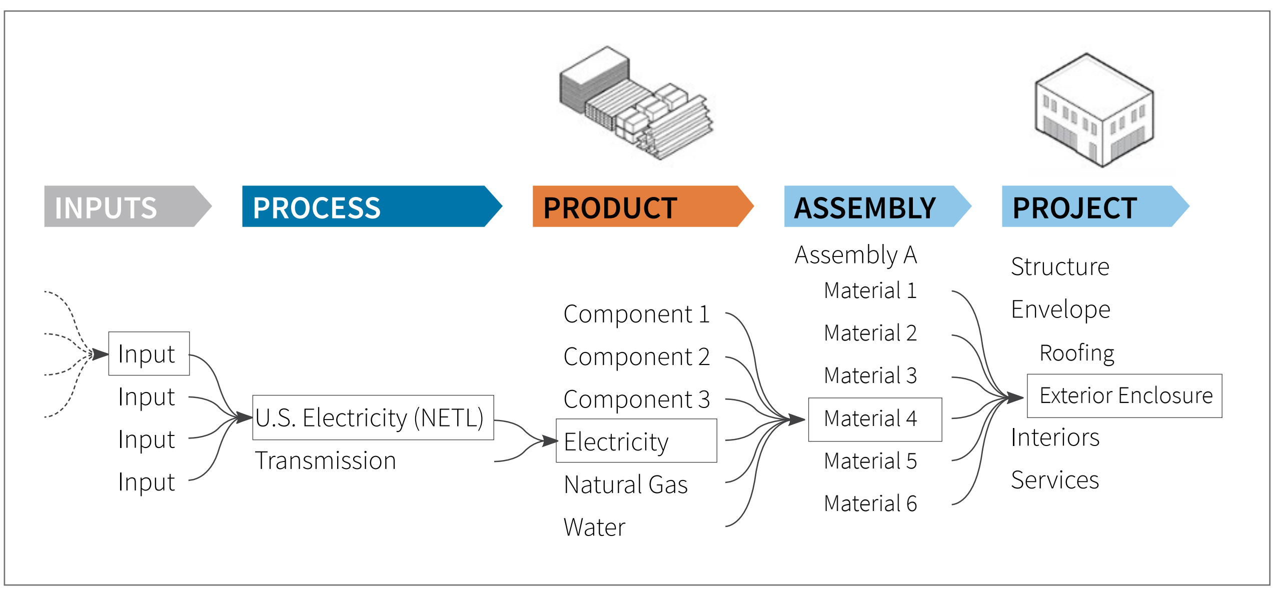

Figure 4. Illustrative example of how LCA models nest into one another. While a project LCA practitioner may think of the environmental impact data for Material 4 as a single data point input into their model of a building, the one data point is from an LCA model composed of inputs from a series of additional LCA models. In LCA terminology, "processes" have inputs and outputs that are "flows," where the output of one process is often an input to another.

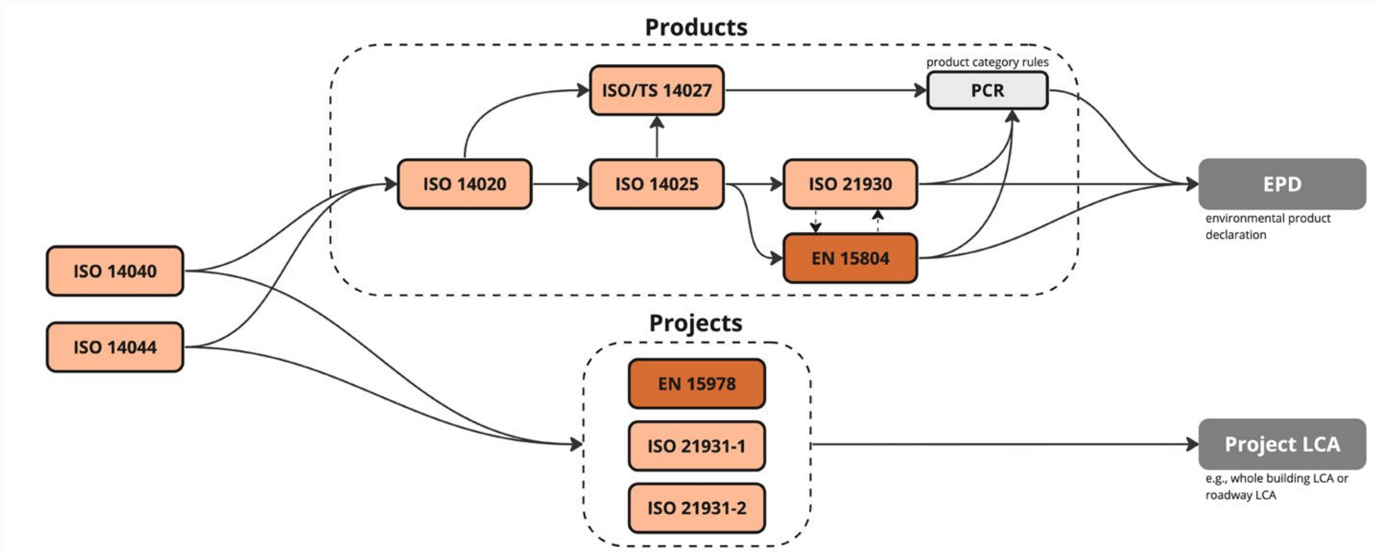

Figure 5. ISO 14040 and ISO 14044 are foundational LCA standards. Multiple families of product and project standards build off of this foundation to provide more specifics.

and services (not just construction-related), relates to product- and building-scale assessments, and includes a wide range of environmental impact categories. ISO amended this standard in 2020, including modifications to some terms and definitions. The amendment is titled: *ISO 14040:2006/Amd 1:2020 Environmental management — Life cycle assessment — Principles and framework — Amendment 1*.

- ***ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines*** builds upon the foundational principles and framework of ISO 14040 to provide the normative requirements for guidelines for conducting an LCA (ISO, 2006b). Aimed primarily at LCA practitioners, this document provides a discussion of the basic components and terminology of LCA (e.g., phases of the study, data quality requirements, allocation methods, impact assessment, etc.). ISO amended this standard in 2020, including modifications to some terms and definitions (similar to the ISO 14040 amendment described above) and the addition of *Annex D Allocation procedures*. The amendment is titled: *ISO 14044:2006/Amd 2:2020 Environmental management — Life cycle assessment — Requirements and guidelines — Amendment 2*.

Life Cycle Impact Assessment (LCIA) methods

An LCIA method includes a list of impact categories (more specifically referred to as "midpoint indicators" in the case of GWP and other TRACI impact categories), definition of how the impacts are calculated (more specifically referred to in ISO 14040 as "classified" and then "characterized"), and in some cases a process for weighting midpoint indicators into high-level endpoint indicators (though this is seldom used in North America). The method also includes or references a dataset of characterization factors per flow per impact category. The Foundational LCA Data Sources section below includes further description of LCIA characterization factors.

Sometimes LCIA methods are referred to as "tools" (e.g., the "T" in TRACI stands for "tool"). As such, LCIA methods don't fit tidily into the standards/data/tools taxonomy used in this report. A brief overview is provided here, with more data-focused discussion of LCIA in Section 2.2.2 below. The EPA provides this explanation:

> LCIA methods are collections of characterization factors, which are measures of relative potency or potential impact, for a given flow (e.g., NH3 to air) for a set of impact categories (e.g., acidification), provided in units of potency or impact equivalents per unit mass of the flowable associated with a given context (e.g., 1.88 kg SO2 eq/kg NH3 emitted to air). LCIA methods are typically used along with life cycle inventory data to estimate potential impacts in life cycle assessment (LCA) (U.S. EPA, 2021).

There are at least eight different LCIA methods.[8] TRACI (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) is the predominant LCIA method

8. The following sites provide further discussion on various available LCIA methods: https://helpcenter.ecochain.com/lcia-methods and https://www.openlca.org/wp-content/uploads/2016/08/LCIA-METHODS-v.1.5.5.pdf.

in North America.[9] Developed by the EPA, it includes seven impact categories (one of which is climate change) plus fossil fuel resource depletion. The most recent version is TRACI 2.1 developed in 2012.

Outside of North America, there is a wider range of LCIA methods. For example, the latest version of EN 15804 includes 13 core impact categories, with characterization factors from a range of sources – Intergovernmental Panel on Climate Change (IPCC), CML, Environmental Footprint (EF), ReCiPe, and others (CEN, 2019). These factors provide clarity in differentiating GHG emission sources (biogenic, fossil, and LULUC) that help enable effective interpretation of LCA results that are not clear when using current TRACI methods, which do not distinguish between these different types of emissions sources. In Europe, the European Commission is responsible for aligning and harmonizing methods and data across LCIA methods (European Commission–JRC–IES, 2011).

2.2.2 Foundational LCA Data Sources

This section includes background data sources appropriate for any LCA (not specific to products, buildings, infrastructure, etc.). Foreground data is specific to a given study, so is not included in this general LCA section. Some of the datasets listed are publicly available, while others are proprietary and only available by purchase.

Historically, public data is transparent but lacks centralized funding and dedicated departments/data developers, which can result in outdated data. Proprietary data lacks transparency but has centralized funding and dedicated data developers, often resulting in more frequent updates.

Public LCI databases, model repositories, and datasets

In the United States, the **Federal LCA Commons** is a collaboration among federal agencies to provide transparent and publicly accessible data and methods to inform life-cycle decision-making. It serves as a central access point for a collection of free public LCA data repositories, including:

- **Federal Elementary Flow List (FEDEFL)**: a "common list of elementary flows for use in federal life cycle inventory and life cycle impact assessment (SOURCE: EPA 2019 Federal LCA Commons Elementary Flow List Report)" (Feraldi, 2023).
- **U.S. Life Cycle Inventory (USLCI)** database (NREL, 2012), operated by the National Renewable Energy Laboratory: a "publicly available LCI database that 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" (Feraldi, 2023).
- **U.S. Electricity Baseline:** codeveloped by NETL, U.S. EPA, and NREL.
- U.S. EPA's **Construction and Demolition Debris (CDD) management datasets:** describe EOL management of common built environment materials, including asphalt pavement, gypsum drywall, wood, concrete, carpet, and others. Include scenarios for landfill, incineration, recycling, etc. (U.S. EPA, 2022).
- U.S. EPA's **US Environmentally-Extended Input-Output (USEEIO) model:** an environmental-economic model of U.S. goods and services (Ingwersen et al., 2022). This report primarily focuses on process-based LCAs. EEIO data captures emissions at an economy-wide scale and care must be taken to combine or compare with process-based LCA data.
- **Other LCI datasets** for wood products, agriculture, biofuels, asphalt pavement, and more.
- **TRACI** and ReCiPe LCIA methods.

In Canada, the **Low Carbon Built Environment Challenge program**, a collaborative effort led by National Research Council Canada and other government agencies and nongovernmental partners, includes goals to expand public Canadian LCI data building off of the work of the Low-Carbon Assets through Life Cycle Assessment (LCA^2) initiative.

In Europe, the European Platform on Life Cycle Assessment (EPLCA) similarly provides public LCA tools and data sources related to the International Reference Life Cycle Data (ILCD) and Product Environmental Footprint (PEF) systems.

A number of European countries also have national LCI databases and related LCA tools, some of which include EPDs. Examples are the German ÖKOBAUDAT database, the Dutch National Environmental Database, the French INIES database, the database in the Swedish Klimatkalkyl tool, and the Swiss KBOB LCA platform. Austria has a suite of nationally funded tools and databases, including Okoindex3, Bau-EPD database, and eco2soft, that work together to provide tools for product and building analysis.

Some **industry associations** (such as worldsteel, Plastics Europe, and Agribalyse) provide publicly available LCI datasets.

9. For example, ISO 21930-2017 Table 5 defines TRACI as the default North American market characterization method (ISO, 2017a).

Public model repositories

The LCA Collaboration Server provides a web repository for openLCA files, facilitating the sharing of LCA datasets and models via the Federal LCA Commons (Kahn et al., 2022). (See a description of openLCA in the next subsection, Professional LCA Modeling Tools.) Such models can serve as templates or building blocks for new LCA models of similar or downstream systems. Transparent, public models also enable other LCA practitioners to better understand the results of an LCA to confirm whether it is a relevant input for their own LCA.

Other key public datasets

- **2017 Commodity Flow Survey** published by the U.S. Department of Transportation Bureau of Transportation Statistics and the U.S. Department of Commerce: provides default transportation values (i.e., typical travel distances for A4) (U.S. Department of Transportation, 2018).
- **eGRID:** EPA's Emissions & Generation Resource Integrated Database provides emissions, emissions rates, generation, heat input, resource mix, and other attributes of nearly all electric power generated in the United States (U.S. EPA, 2023).
- **WARM:** EPA's Waste Reduction Model provides estimates of GHG emissions, energy, and economic impacts for materials' EOL based on different waste management practices. A small number of construction materials are included in the most recent version of the WARM model.
- **AP-42:** EPA's Compilation of Air Pollutant Emissions Factors contains emissions factors and process information for more than 200 sectors and processes (e.g., wood residue combustion in boilers, primary copper smelting, lime manufacturing, etc.).
- **GREET Model:** The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model simulates emissions and energy use of various vehicle and fuel combinations. It was developed by Argonne National Laboratory (ANL) and sponsored by the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy.
- **MOVES:** EPA's Motor Vehicle Emission Simulator estimates GHG (and other) emissions for mobile sources at the national, county, and project level.

Proprietary datasets

Proprietary LCI databases such as ecoinvent and GaBi are available to customers who purchase a license. In addition to requiring a license to use these databases, there are limits on how LCA models and results can be shared when developed using proprietary data.

LCA is composed of nested models, but most construction-focused LCA tool users (using, e.g., EPD generators or WBLCA tools) typically see only the outputs of those nested models as single data points. (They do not see the underlying processes and flows.) Proprietary LCA models may be required to generate the impact results that are used in an EPD or as a building block for other models, but they are typically not transparent or available for public use. They can differ between versions and give different results depending on which modeling software they're used in (Miranda Xicotencatl et al., 2023), and they can also be constructed with significant variation in LCA methods such as decisions related to allocation of impacts between co-products or treatment of recycling.

LCIA characterization factors (e.g., TRACI)

As mentioned above, an LCIA method such as TRACI can be considered as a set of LCIA impact categories. For each *impact category* (e.g., climate change), there is an *indicator* – that which is measured (e.g., GWP) and a given unit to measure that indicator (e.g., kg CO_2e). A *characterization factor* provides quantification for how impactful a given unit of a substance's emission to nature is for a given impact category (e.g., 25 kg CO2e per kg of methane emitted to air). This allows for the mapping of a flow from the inventory (e.g., 10 kg methane emission to air) to the measured indicator (e.g., 250 kg CO2e).

Table 1 provides examples of three (of many) climate change characterization factors as used in TRACI 2.1 and an example use. TRACI includes nearly 4,000 substances, each with a characterization factor per impact category.

Table 1. Example LCIA characterization factors in use. The simplified example assumes one process that emits three climate-change-causing substances to the air.

LCIA method	TRACI 2.1		
Impact category	Climate change		
Indicator (unit)	GWP (kg CO_2e)		
Substance	**Characterization factor** (kg CO_2e / kg emission)	**Example emission** (kg)	**Example impact** (kg CO_2e)
Carbon dioxide (CO_2)	1	100	100
Methane (CH_4)	25	10	250
Nitrous oxide (N_2O)	298	1	298
Total	–	–	648

2.2.3 Professional LCA Modeling Tools

The following LCA modeling tools are capable of sophisticated assessment and are typically used by LCA professionals with significant experience. In contrast, many of the product- and project-oriented tools in the later sections of this report provide simplified modeling opportunities for the non-LCA-professional user.

- **openLCA** is a free, open-source professional LCA software that allows users to connect to a vast number of datasets (nearly 100,000), including the public and private LCI datasets described above (GreenDelta, 2022).
- **SimaPro** and **GaBi** are two popular proprietary primary LCA modeling tools. PRé Sustainability develops SimaPro and also develops the proprietary ecoinvent database (though one can use ecoinvent data in other tools, and other data besides ecoinvent in SimaPro) (PRé Sustainability, 2023). GaBi LCA software, developed by Sphera, is built on the proprietary Sphera Managed LCA Content (formerly known as "GaBi") databases (Sphera, 2023).

2.2.4 Key Actors/Organizations

Some key actors in the foundational LCA ecosystem include:

- **LCA practitioners/professionals** that perform, review, and verify LCAs;
- **federal agencies** that generate, manage, and curate public data. In the United States, this includes the agencies that collectively manage the Federal LCA Commons. This public resource is significant to the future of U.S. LCA-based policies, and receives much attention in the Solutions section of this report. Similarly, Canadian federal agencies such as National Research Council Canada play a critical role in supporting publicly available LCI and LCA data;
- **policymakers** that fund staffing and maintenance of the public data sources described above;
- **NGOs and academics** that contribute to public data repositories, conduct studies using LCA, develop and test LCA methods and results, and train LCA practitioners in university programs;
- **database and tool developers** of both proprietary and open-source datasets and tools;
- the **American Center for Life Cycle Assessment (ACLCA)**, which is a nonprofit membership organization focused on education, awareness, advocacy, and communications around environmental LCA. The ACLCA is an important organization in the United States for collecting and communicating with LCA practitioners. It manages several professional certifications for LCA practitioners, convenes topic-focused committees (such as its PCR committee), and publishes guidance documents in order to educate and build consensus around complex LCA topics;
- **industry trade organizations**, as many industries support the generation of LCA data and PCR development for materials and products produced by their members. They typically compile data from members to produce industry-average EPDs and can provide data to the USLCI and other LCI datasets.

2.3 Product LCA and EPD Ecosystem

The product LCA ecosystem builds on the foundation discussed above to assess products or materials. A Type III EPD (generally referred to simply as an "EPD") is a third-party-verified document that reports the environmental impacts of a product based on the results of an LCA. Buy Clean and similar procurement-focused embodied carbon policies in North America use EPDs as the reporting mechanism (Lewis et al., 2022). This section therefore focuses on the creation and use of EPDs. Other product embodied carbon reporting schemes exist – such as GHG Protocol's Product Standard (WRI & WBCSD, 2011) and Europe's PEF method (Zampori & Pant, 2019) – but are not the focus here.

2.3.1 Product Standards and Guidelines

International standards

In North America, the development of EPDs and PCRs is governed by a number of ISO standards and technical specifications[10] that build on ISO 14040 and ISO 14044 described in the General LCA Standards section, including ISO 14025, 14027, 14067, and 21930.

- ***ISO 14025:2006 Environmental labels and declarations — Type III environmental declarations — Principles and procedures*** provides the framework for EPDs, which ISO formally refers to as "Type III environmental declarations" (ISO, 2006c). In contrast with lesser-used Type I and Type II environmental claims (governed by different ISO standards), Type III claims contain quantified product information based on life cycle impacts and must be third-party-verified. One key component of ISO 14025's framework in relation to Buy Clean policy is the explicit goal of comparability: Type III declarations "are intended to allow a purchaser or user to compare the environmental performance of products on a life cycle basis. Therefore comparability of Type III environmental declarations is critical." EPD comparisons are appropriate "between products fulfilling the same function," meaning that appropriate comparison at the EPD level is generally within (and not across) product categories.
- ***ISO/TS 14027:2017 Environmental labels and declarations — Development of product category rules*** provides the framework for developing, reviewing, and updating PCRs in alignment with ISO 14040, ISO 14044, ISO 14025, and ISO/TS 14067. Unlike ISO 21930, ISO/TS 14027 is not specific to construction products. ISO developed this technical specification with the aim of providing more standardization and consistency across PCRs (Minkov et al., 2015).
- ***ISO 21930:2017 Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services*** provides core requirements for EPDs of construction products and services, particularly in North America. Sometimes referred to as the "core PCR" (including in its own text), ISO 21930 forms the basis for more specific "subcategory" PCRs (i.e., PCRs for particular construction product categories, such as concrete, wood products, and flooring). Some key aspects of ISO 21930 include:
    - defining how EPDs can be used for comparison of construction products (in the context of the construction project);
    - ensuring that EPDs provide verifiable and consistent data related to product information, LCA methods, and scenarios;
    - providing requirements for EPDs based on average data (e.g., across multiple similar products or facilities).
- ***EN 15804:2012+A2:2019: Sustainability of construction works — Environmental product declarations — Core rules for the product category of construction products*** is Europe's parallel standard to ISO 21930 that provides core PCRs for the development of construction product EPDs and forms the basis for more specific European PCRs (CEN, 2019). The most recent version of EN 15804 (2019) and ISO 21930:2017 are aligned in most aspects, but there are some differences that render them not fully compatible, as outlined in Table 2 (page 20).

Product category rules (PCR)

A PCR is a set of specific rules, requirements, and guidelines for developing Type III environmental declarations for one or more product categories. PCRs are reviewed and improved periodically over time. Each category's PCR dictates methodological decisions that are relevant and fine-tuned to the material supply chain of that product category (e.g., concrete, floor coverings, insulation, etc.). A PCR dictates which life cycle stages and scopes must be included in the LCA, which background data sources are acceptable or mandatory, which processes and flows may be included or excluded, and other modeling choices such as allocation method and impact assessment method that can strongly influence model results.

10. An ISO "technical specification" (with label ISO/TS in its title), unlike an ISO international standard, "addresses work still under technical development, or where it is believed that there will be a future, but not immediate, possibility of agreement on an International Standard. A Technical Specification is published for immediate use, but it also provides a means to obtain feedback. The aim is that it will eventually be transformed and republished as an International Standard" (ISO, 2023).

Table 2. Summary of several key differences between ISO 21930:2017 and EN 15804:2012+A2:2019 that hamper comparability.

Topic	ISO 21930:2017	EN 15804:2012+A2:2019
Impact categories	5 mandatory impact categories (ISO 21930:2017 Table 5)	13 core (mandatory) environmental impact categories + multiple other optional categories (EN 15804:2012+A2:2019 Table 3)
Scope – which life cycle stages are included	A1–A3 required; other stages optional (varies depending on PCR) Menu of EPD types: cradle to gate; cradle to gate with options; cradle to grave Module D always optional (ISO 21930:2017 § 5.2.2)	A1–A3, C1–C4, D required (with some exceptions if multiple criteria are met and justification provided); other life-cycle stages optional. (EN 15804:2012+A2:2019 § 5.2)
Biogenic carbon reporting	NOT a separate climate change impact category (ISO 21930:2017 Table 5)	Separate climate change category and indicator – GWP-biogenic (EN 15804:2012+A2:2019 Table 3)
Treatment of process (“pre-consumer”) scrap metal[11]	Modeled as secondary material to be recycled, same as post-consumer scrap (i.e., as “waste,” with no environmental burden in LCA) (ISO 21930:2017 § 7.2.6)	Modeled as co-product, with allocation applied (i.e., as having economic value, with environmental burden in LCA) (EN 15804:2012+A2:2019 § 6.4.3.3)
LULUC impacts	NOT a separate climate change impact category To be included in GWP calculation “when significant,” and declared separately as additional environmental information (ISO 21930:2017 § 7.2.11)	Separate climate change category and indicator – GWP-luluc; Includes description and guidance (EN 15804:2012+A2:2019 Table C.1, § C.2.5)
Average EPDs	Guidance, requirements, and examples for average EPDs (e.g., a manufacturer’s EPD that covers a range of similar products or several of the manufacturer’s plants, or an industry-average EPD that covers several manufacturers’ plants) (ISO 21930:2017 § 5.3 and Annex B)	No explicit requirements or guidance related to average or sector EPDs

In North America, there are several “program operators” (entities that oversee the creation and publication of EPDs), most of which operate as for-profit businesses. Examples include NSF International, UL Environment, and SmartEPD. Generally, the creation of a PCR is funded by an industry trade organization that has a great deal of influence on the underlying rules and content of the PCR. There is no single body that is responsible for harmonization across PCRs, and as such, presently, efforts to harmonize rules across product categories are challenged.

A large number of PCRs are relevant for policy, depending on the scope of products included in the policy. For example, a policy that includes concrete may require that concrete EPDs submitted meet the requirements of the NSF International Concrete PCR. However, the NSF International PCR for Portland, Blended, Masonry, Mortar, and Plastic (Stucco) Cements, the ASTM PCRs for Slag Cement and Precast Concrete, and UL Environment’s PCR for Expanded Shale, Clay, Slate, and Lightweight Aggregate are all relevant upstream PCRs.

Appendix B provides a list of PCRs relevant to current U.S. embodied carbon policies.

Guidance documents

In 2022, the ACLCA released PCR Guidance – also called the “ACLCA PCR Open Standard” – to promote the quality and consistency of PCRs (ALCLA, 2022). To conform with the voluntary Open Standard, PCRs must meet several criteria related to the PCR development process and committee, the content of the document, and the verification process. There are three levels of conformance that correspond to three different EPD use cases, where each successive level must meet more stringent requirements to conform: (1) for transparency, (2) for procurement, and (3) as a data source.

The ACLCA toolkit includes multiple addenda on more specific topics, including *Assessing Data Quality of Background LCI Datasets, Allocating Burdens and Benefits of Materials Shared Across Product Systems,* and *Quantifying Renewable Electricity*

11. The following report describes this issue in thorough detail. Sections 7.3–7.5 focus on ISO 21930 and EN 15804. International Aluminum. (2023). *Aluminium Scrap in Carbon Footprint Calculations.* https://international-aluminium.org/wp-content/uploads/2023/01/Carbon-footprint-of-recycled-aluminium-IAI-Document-Public-Review-Final.pdf

Instruments in Environmental Product Declarations. Upcoming addenda in development will cover biogenic carbon accounting, digital EPDs, and data specificity in EPDs.

2.3.2 Product LCA Data Sources

Foreground data for product LCAs

A manufacturer or industry association that performs a product LCA to create an EPD collects primary "foreground" data on the processes over which it has operational control. Examples of **foreground data for a product LCA include:**

- quantities and types of raw materials and fuels entering the facility
  - e.g., 1,000 kg quarried feldspar rock, 100 therms of natural gas
  - used for A1 calculations
- associated distances and modes of transport for items entering a facility
  - e.g., 100 km by rail
  - used for A2 calculations
- facility energy use: on-site and grid supplied
  - e.g., 1,000 kWh grid supplied electricity
  - used for A3 calculations
- process emissions (not due to energy consumption) from facility
  - e.g., CO_2 emissions due to calcination during cement production; foam blowing agent emissions
  - used for A3 module calculations
- additional product performance and physical attribute data as relevant
  - e.g., product service life, maintenance data, material makeup of product
  - used for B, C, and D module calculations
- quantities of material leaving facility: product being assessed, plus any co-products and/or wastes
  - e.g., quantity of paper-faced mineral wool batt insulation; quantity of other products and wastes produced at the same facility
  - used to allocate a portion of the total facility operations to the product being assessed per declared unit.

Background data for product LCAs

To build out the product LCI, this primary data is combined with background data as described in Section 3.2, including the following **background LCI data:**

- A1 module: emissions per unit of raw material/input ingredient (e.g., emissions per kg of quarried feldspar rock)
- A2 module: emissions per unit of transport (e.g., emissions per tonne-km rail transport)
- A3 module: emissions per unit energy consumed (e.g., emissions per grid-specific kWh of electricity consumed, or per therm natural gas combusted)
- B, C, and D modules: scenarios and LCI data for use, disposal, and recycling.

These background LCI data points vary in their origin (e.g., public and/or private data sources) and in their specificity. The degree to which a given source is prescribed or prioritized depends on the particular product category and its associated PCR.

In some cases, a product LCA for an EPD may use a constituent ingredient's EPD as supply-chain-specific background data. For example, a processed glass LCA may incorporate a flat glass EPD published by the particular flat glass supplier for that processed glass product. Or a concrete LCA may incorporate a cement EPD to represent the specific cement product used in the concrete. Note that the appropriate use of EPDs as data sources ideally requires a degree of harmonization across PCRs, as outlined in the ACLCA's PCR Open Standard and described elsewhere in this report.

2.3.3 Product LCA Tools – EPD Generators and EPD Databases

Creators of EPDs may use any of the primary LCA tools described above, such as openLCA, SimaPro, GaBi. They also may use tools specifically developed for EPD generation. "EPD generators" allow manufacturers to input primary data specific to their product, company, and operations into a template and allow the tool to perform the necessary background calculations to generate the EPD.

Examples include the Climate Earth tool for concrete EPDs, the Emerald Eco-label EPD tool for asphalt mixes, and the One Click LCA pre-verified EPD generator, which is non-industry-specific and uses the EPD Hub for publication and verification.

In addition to EPD generation tools, there are also tools for EPD databases aimed at EPD users, such as Building

Transparency's Embodied Carbon in Construction Calculator (EC3) tool (a free open-access database) and One Click LCA's EPD database (accessible via paid license).

2.3.4 Key Actors/Organizations

Some key actors in the EPD data ecosystem include:

- **program operator:** the organization that develops and publishes PCRs and/or certifies EPDs in accordance with those PCRs and appropriate standards (e.g., ISO 21930);
- **PCR committee**: the group of stakeholders that work together to develop or update a PCR. The committee typically includes industry association and manufacturing representatives, and ideally also includes other stakeholders and experts from academia, government, and NGOs;
- **PCR/EPD verifier**: who ensures that PCRs and EPDs are independently verified, to demonstrate conformance with the relevant standards;
- **industry/trade associations:** which may publish an IW-EPD and/or provide technical and other support to association member companies to produce their own EPDs. Industry associations or groups of manufacturers also contribute data that is used in public and proprietary datasets and must report production data. In the case of concrete, the National Ready Mixed Concrete Association is also a program operator for concrete EPDs (for development of EPDs, not development of PCRs).
- **government (federal) agencies:** which develop and maintain many public datasets such as those described in 2.2.
- **manufacturer**: the company initiating and funding the creation of the EPD.
- **LCA practitioner:** the person (or group) who does the LCA data collection and modeling. Practitioners may be in-house (working for the manufacturing company producing the EPD) or consultants;
- **standards technical committees**: those collections of tech nical experts from different fields and different countries that collaborate to produce and update the standards that define the rules of product LCA – e.g., the relatively recent ISO 14027 and the potential future update of ISO 21930.

Mapping the EPD Ecosystem for Construction Products

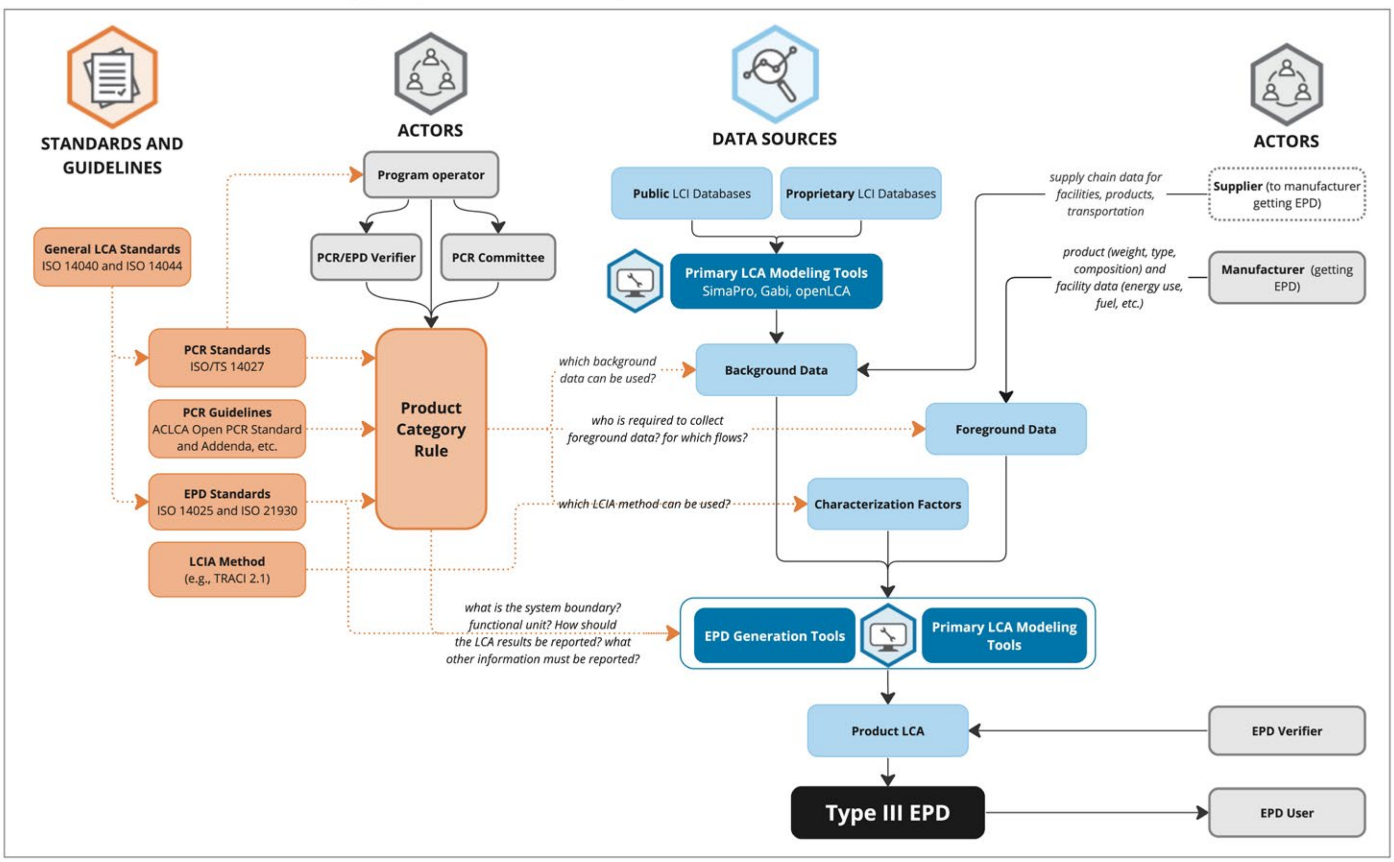

Figure 6. Mapping the EPD data ecosystem for construction products.

2.4 Project LCA Ecosystem – Buildings

There are two main scales of LCA-based embodied carbon policies – the product scale, discussed in the section above, and the project scale covering construction projects as they are designed and built. This report distinguishes between two types of project-scale LCAs. The first is buildings, described here, and the following section discusses infrastructure.

2.4.1 Building LCA Standards

There are several international standards for WBLCA that build upon the more general ISO 14040 and ISO 14044 standards to provide an LCA framework for buildings. ISO 21931-1:2022 is used in North America (ISO, 2022).

- ***ISO 21931-1:2022 Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment — Part 1: Buildings*** (or "ISO 21931 Part 1") provides a framework for sustainability assessment of social, economic, and environmental performance of whole buildings. (Part 2 of the standard applies to civil works, and is described below in the Roadway section of this report.) This standard specifies what to include in WBLCA modeling and reporting of new and existing buildings. Significant topics include the object of assessment, system boundary, life cycle stages, environmental impacts, social/economic impacts, methods for quantification, and reporting requirements. The standard provides comprehensive requirements on what to include in WBLCA, but limited guidance on how it should be implemented by LCA practitioners.
- ***Proposed ASHRAE/ICC Standard 240P — Evaluating Greenhouse Gas (GHG) and Carbon Emissions in Building Design, Construction and Operation*** will provide a quantification method for evaluating and reporting GHG emissions of a building over its full life cycle. The standard will establish minimum modeling standards, including consistent procedures, data, and reporting formats that can be referenced by policies, codes, and other standards that address new and existing building performance. The standard will cover both embodied and operational emissions.
- ***ASTM E2921-16a Practice for Minimum Criteria for Comparing Whole-Building Life Cycle Assessments for Use with Building Codes, Standards, and Rating Systems*** was published in 2016, but this has not been widely adopted or used in policies in the United States (ASTM, 2016). This standard mostly directs users to ISO 14025, ISO 14040, ISO 14044, and ISO 21930 for general methodologies and processes of LCA while filling in a few gaps that ISO leaves open to interpretation.
- ***EN 15978:2011 Sustainability of construction works — Assessment of environmental performance of buildings*** is the primary European WBLCA standard that provides calculation rules for assessing the environmental performance of new and refurbished buildings (CEN, 2011). Similar to ISO 21931-1 in many ways, EN 15978 is generally more detailed and descriptive, providing specific requirements and examples for many topics and procedures, including:
  - the appropriate use of EPDs to provide quantified environmental product data to the WBLCA (a more common practice in Europe than in North American WBLCAs);
  - physical scope and system boundary;
  - specific scenarios for construction, use, and EOL by life cycle module;
  - calculation rules (regarding, e.g., B6 operational energy and C3 waste processing);
  - gross material quantities (accounting for, e.g., construction waste);
  - replacement rates for components;
  - methods for determining the reference study period (RSP) for the building assessment;
  - and many other components of WBLCA.
- ***Royal Institution of Chartered Surveyors (RICS) Whole Life Carbon Assessment for the Built Environment (2017)*** is a detailed and prescriptive document that sets out specific mandatory principles and supporting guidance for the whole-life carbon accounting of buildings (i.e., operational and embodied carbon). The document aims to provide a consistent accounting and reporting framework in line with EN 15978 for built projects and to enable better reliability, comparability, and usability of results from whole-life carbon assessments. While this standard is intended primarily for a UK audience, it is globally applicable (to all RICS members) and geographic adjustments are highlighted to enable the requirements and guidance to be applied outside the UK. Examples of significant components include:
  - description of WBLCA methods as they relate to traditional AEC design phases and practices, as well as the BREEAM® (Building Research Establishment Environmental Assessment Methodology) and the

LEED (Leadership in Energy and Environmental Design) rating systems;

- baseline material specifications to be used for baseline comparison scenarios;
- default transportation distances for products and materials;
- average values for construction site emissions (module A5);
- expected lifespans for common products;
- typical recovery rates for EOL scenarios;
- requirements for accounting and reporting of biogenic carbon and carbonation; and
- a reporting template as an appendix.

Updated versions of both EN 15978 and the RICS Whole Life Carbon Assessment for the Built Environment are currently in draft form and are expected to be published soon. In Europe, additional national LCA standards or methodologies exist in Denmark, Germany, Finland, Sweden, Norway, the UK, and the Netherlands, as well as across Europe via Level(s) (Astle et al., 2023).

Building LCA modeling and reporting guidelines

Building LCA modeling and reporting guidelines are typically nonmandatory documents that provide recommendations, general direction, and advice for the technical criteria, methods, processes, and practices of WBLCA. Guidelines can be developed by any entity and do not require the formal consensus of technical experts. The following examples have been developed by national or municipal agencies. Though not included here, the private sector has also developed WBLCA guideline documents.

- ***Natural Research Council Canada Guidelines for Whole-Building LCA version 1.0*** (2021) proposes a methodology, instruction, and interpretation of EN 15978:2011 and ISO 21931:2017 for WBLCA practitioners to support standardization of WBLCA practice, provide a framework for WBLCA performance benchmarks, improve harmonization across different WBLCA software tools, and support WBLCA compliance schemes in policy and green building programs.
- ***City of Vancouver DRAFT Embodied Carbon Guidelines v0.2*** (2023)[12] provide guidance on demonstrating compliance with embodied carbon requirements in the Vancouver Building By-law, and may also be used by requirements in policies or programs to calculate or reduce embodied carbon in construction. The City Council approved changes in the Vancouver Building By-law in May 2022 to require designers to calculate, limit, and later reduce, embodied carbon in new Part 3 buildings, referencing these guidelines to support compliance. These guidelines also reference and build off of the National Research Council of Canada (NRC) guidelines for WBLCA described above.[13]

In addition to these modeling guidelines, there are a number of guidelines that are solely focused on how the embodied carbon (or whole-life carbon) results of an LCA are reported for buildings, such as the WBCSD Building System Carbon Framework (WBCSD, 2020), the Greater London Authority's Whole Life-Cycle Carbon Assessments Guidance (GLA, 2022), the London Energy Transformation Initiative (LETI) Embodied Carbon Reporting Template (LETI, 2022), and Building Transparency's ongoing "Open Carbon Building Data Format" project.

Reporting frameworks dictate how embodied carbon results from a building LCA should be reported, rather than how they should be calculated. Information typically included in a reporting framework includes:

- project data (location, climate zone, floor area, building height and stories, building use and type, seismic design category, construction type, etc.);
- LCA model information (which tool was used, RSP, scope included, background datasets used, etc.);
- LCA results (e.g., GWP results broken down by life cycle stage, physical scope element, or other categorizations).

Harmonized reporting frameworks are an important step toward achieving a central database of building LCA results for benchmarking, but they must be complemented by harmonized building LCA calculation and methodology guidelines or they will not result in harmonized datasets of results.

2.4.2 Building LCA Data Sources

Whereas product LCA is often limited to the product stage (modules A1–A3), building LCA typically includes the product, construction (A4–A5), use (B), and EOL (C) stages, and sometimes supplementary information beyond the building life cycle (D). Due to this expanded scope (beyond initial construction), building LCA practitioners must consider the length of time and the typical EOL for the products and building as a whole, including:

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12. Not published at the time of this writing, but will be available at https://vancouver.ca/green-vancouver/zero-emissions-buildings.aspx.

13 At the time of preparing this report, the City of Vancouver plans to release a new version of the guidelines (v0.3) and a spreadsheet-format EC Design Template in the near future (Z. Teshnizi, personal communication, July 28, 2023).

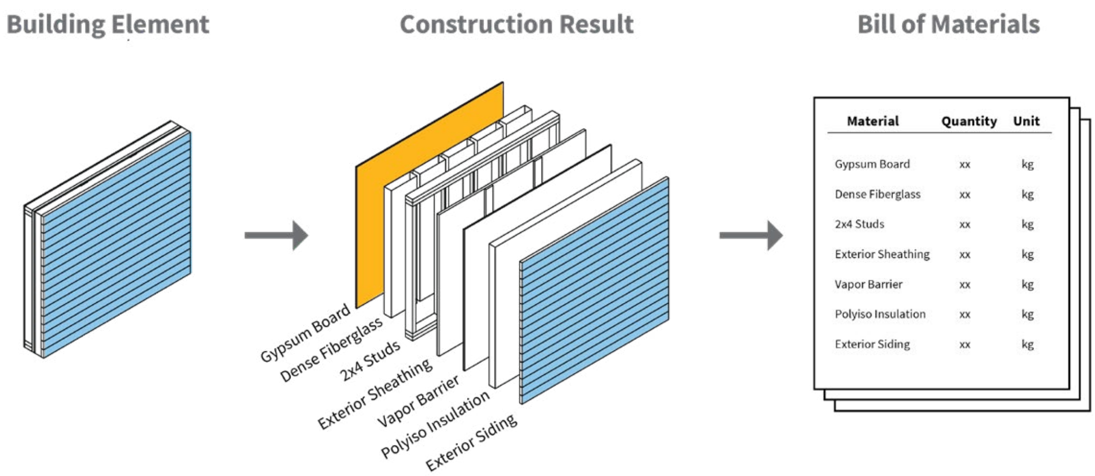

Figure 7. Building LCA tools can help practitioners translate digital building elements into a bill of material quantities that is required for an LCA.

- ***Service life:*** period of time after installation during which a building or its component parts meet or exceed the performance requirements (ISO 21931-1). Also referred to as "design life" in ISO 21930 and "working life" in EN 15978.
    - E.g., ## years before carpets, wallboard, windows, etc. are expected to be replaced.
    - For some materials, such as structural materials, this is likely the same (or longer) than the service life of the building.
    - Includes subcategories: reference service life (RSL) = product lifespan under reference conditions; and estimated service life (ESL) = product lifespan under conditions specific to the building and its use (ISO 21930:2017).
    - Some EPDs that include B-stage (use) impacts include product service life data.
- ***Reference study period (RSP):*** period over which relevant aspects and impacts of the building are analyzed (ISO 21931, EN 15978).
    - E.g., a 50-year, 60-year, 75-year, or 100-year study period.
- ***End-of-life (EOL) treatment:*** whether a product is typically landfilled, recycled, incinerated, etc.
    - E.g., XX% of wood is sent to landfill, XX% is incinerated, XX% is recovered.
    - Sometimes included in EPD if the scope is cradle to grave.

Foreground data for building LCA

The architect, engineer, green building consultant, or other practitioner completing the building LCA collects primary "foreground" data on the building's design, materials, and construction process. Such foreground data includes:

- Quantity/type for each material or assembly used in the building:
    - e.g., area and type of concrete masonry unit (CMU) wall assembly, ## m3 of ⅝" thick plywood;
    - typically estimated from building information model (BIM) software (e.g., Revit), quantity take-offs based on architectural drawings, or from a bill of materials (BOM) provided by a contractor. Building LCAs are often done during design, when 'as-built' quantities are not yet available. See figure 7.
- Site characteristics:
    - e.g., climate, soil, and site properties, seismic design category;
    - can support benchmarking purposes.
- Transportation estimates:
    - e.g., vehicles used and distance traveled to deliver materials;
    - used for estimating impacts of transporting materials to the construction site (A4). If transportation data is not provided, then WBLCA tools typically include generic A4 data based on typical distances for this product type.
- Construction and installation data, including site electricity use, water use, equipment and fuel usage for

excavation, demolition, and construction (if collected):
  - e.g., ## kWh electricity, ## gallons/type of fuel consumed, etc.;
  - may also include material inventory for temporary works and construction waste (e.g., ## m3 of ⅝" thick plywood for concrete formwork, etc.);
  - used for A5 calculations.
  - Note: Data estimating construction impacts is difficult to find for North American construction, and A5 impacts are therefore regularly either very rough estimates or left out of the scope entirely of most WBLCA studies, depending on the WBLCA tool (Pearson and Waters, 2023).
- Service life data for products, as indicated by manufacturer, industry trade organization, and/or independent surveys:
  - e.g., XX years of service life for paint;
  - used for B4 calculations. If custom input is not provided, WBLCA tools typically include service life assumptions for each product that are based on typical use.
- Selection of regionalized data, when available:
  - e.g., GHG emissions of regional electricity grid, regional variations in standard heating and cooling energy sources and systems.

Background data for building LCA

Building LCA background data sources typically include:

- Underlying LCA datasets built into WBCLA tools such as tallyLCA, One Click LCA, and Athena:
  - The most common background data source for building LCA is the dataset in the WBLCA tool. WBLCA tools assemble background data models, include nested LCA models for specific materials and processes, and also include assumptions for transportation type (e.g., barge, rail, truck) and distance traveled, construction waste factors, EOL treatment, and service life assumptions.
- Public building material databases:
  - e.g., EC3, Built Environment Carbon Database (BECD), GREET building material modules.
- EPDs for industry-wide, product-specific, or facility-specific manufacturing of products:
  - Additional life cycle stages may need to be added to be included.
  - Ideally, use of EPDs as data sources requires a degree of harmonization across PCRs and WBLCA methodology, as outlined in the ACLCA's PCR Open Standard and described elsewhere in this report.
- Public (e.g., Federal LCA Commons, USLCI) and proprietary (e.g., EcoInvent, GaBi) background LCI Databases, as described in section 2.2.2.
- Publications, reports, or other estimates.

When modeling a full building over a long period of time (typically 50–75 years, depending on the standard or requirements the modeler is following), an LCA modeler needs data to support many assumptions beyond just the quantity of materials and their emissions factors, such as how long the materials will be used before being replaced, how many miles they will be transported to the site and with what equipment, how the material will be treated at the end of life, and many more. These are referred to as "scenarios," and an LCA modeler needs the background data to develop these scenarios to be accurate, up to date, and nuanced enough to represent their project spatially and temporally. Often, this data is difficult to find. For example, the U.S. EPA's CDD management datasets describe EOL management of common built environment materials, but they are not specific to geographic region, do not provide the full breadth of EOL scenarios for construction materials, and need additional funding to be regularly updated.

Data Specificity and WBLCA

Building LCAs can be helpful for measuring the *potential* benefits of design and procurement decisions, service life decisions, and EOL treatment. However, before procurement and construction, generic or industry-average data may be preferred for policy disclosure, depending on the timing of the assessment in relation to the building's design/construction timeline (e.g., during concept design, detailed design, or after completion). For example, claiming the carbon benefits from a specific manufacturer and facility using an EPD may be green-washing if the product does not end up installed in the building due to construction changes.

The preferred data type may vary depending on when disclosure is required (e.g., before or after product selection has occurred). Table 3 summarizes preferred data types at various points during the assessment process, based off guidance from international standards.

2.4.3 Building LCA Tools

It is possible to use primary LCA modeling tools (openLCA, SimaPro, and GaBi) to model an entire building. But because buildings are such complex objects (compared to products), developers have created WBLCA

Table 3. Preferred types of data at various points during the assessment process, adapted from EN 15978 (2011) and RICS *Whole-Life Carbon Assessment for the Built Environment* (2017).

* Item differs from EN 15978. For construction stage and as-built LCA, this report places preference on using more specific (e.g., product- and facility-specific) data where available and confirmed to match the actual products used. In other cases, generic or average data is appropriate. This differs from EN 15978:2012, which identifies generic and average data as equally preferable to specific data.

Type of data	Point of assessment during building life cycle stage		
	Concept design	Design completion ("As designed")	Construction completion ("As built")
Generic data Data sourced from a third-party LCI database or other source, not directly measured/collected	✓	✓	*Alternative source if preferred option(s) not available**
Average data Data averaged across multiple manufacturers or sites, such as an industry-average EPD	✓	✓	*Alternative source if preferred option(s) not available**
Specific data Data specific to a manufacturer's product and/or facility and/or supply chain	*Alternative source if preferred option(s) not available*	✓	✓
Measured data Data from direct measurement, such as vehicle fuel usage or material quantities based on receipts		✓	✓

software tools specifically for professionals to use during design.

In addition to including LCI data on primary materials and manufacturing processes, WBLCA tools also help users convert complex assemblies into lists of material quantities that are usable for analysis (e.g., converting a discrete area of a curtain wall assembly with specific visual, acoustic, and thermal performance into quantities of individual materials such as glass, metal trim, gaskets and sealants, metal panel, insulation, vapor barriers, and coatings). WBLCA tools also contain data on construction, use, and EOL scenarios that is omitted from most product EPDs.

Some of the widely used software tools in North America specifically developed to support WBLCA include:

- **Athena Impact Estimator for Buildings** is a freestanding software package developed in Canada that can be used to complete WBLCA or to compare building assemblies and materials. It includes most standard materials for structure and enclosure and some finish materials. LCA data is based on Athena's database (not EPDs).
- **One Click LCA** is a suite of tools that allow input of building material quantity data manually or via integrations with other software. It includes a database of product EPDs, IW-EPDs, and regionalized generic data. Which tool in the suite is being used determines which inputs are available (e.g., EPDs that use a certain LCIA method), default modeling assumptions (e.g., building service life), and outputs (e.g., which impact categories it reports).
- **tallyLCA** is a plug-in for Revit (BIM software) that performs iterative WBLCA natively within a design and documentation model. The tool simplifies the process of quantifying materials to compare building design options and assemblies and reports total embodied carbon and other environmental impacts during design for a wide range of materials. tallyLCA's background database is built on GaBi data (not EPDs).

In addition to these tools, there is a growing variety of web-based calculators and design tools to enable early-design-stage analysis of carbon impacts. For example, the EPIC (Early-Phase Integrated Carbon) calculator uses basic building information to apply embodied and operational carbon intensities to define a baseline scenario and allow users to apply predefined reduction strategies to test their carbon savings and to establish project benchmarks. The CARE (Carbon Avoided: Retrofit Estimator) tool allows users to compare the operational and embodied carbon impacts of renovating an existing building vs. replacing it with a new one. A non-exhaustive list of tools can be found on the AIA-CLF Embodied Carbon Toolkit homepage under "Tools for Measuring Embodied Carbon."

Table 4. Summary of differences in reporting for life cycle stages for Athena Impact Estimator, One Click LCA, and tallyLCA. Blue indicates information that is reported and included in the tool output that can be viewed by the tool user. Yellow indicates data that is reported optionally. Optional user input data requires a tool user to input values, such as quantity and type of fuel used. WBLCA tools are frequently updated and the following reflects only a point in time of specific tool versions.

<table>
<tr><th></th><th></th><th colspan="3">Building LCA Tool</th></tr>
<tr><th></th><th></th><th>Athena Impact Estimator</th><th>One Click LCA for LEED & Life Cycle Carbon - Global**</th><th>tallyLCA</th></tr>
<tr><th></th><th></th><th colspan="3">Tool Outputs: Life Cycle Stage Reporting</th></tr>
<tr><td>A1</td><td>Raw material supply</td><td>Reported</td><td rowspan="3">Combined (A1–A3)</td><td rowspan="3">Combined (A1–A3)</td></tr>
<tr><td>A2</td><td>Transport</td><td>Reported</td></tr>
<tr><td>A3</td><td>Manufacturing</td><td>Reported</td></tr>
<tr><td>A4</td><td>Transport</td><td>Reported</td><td>Reported</td><td>Reported</td></tr>
<tr><td>A5</td><td>Installation & assembly</td><td>Reported*</td><td>Life Cycle Carbon tool only</td><td>Optional (user input)</td></tr>
<tr><td>B1</td><td>Use</td><td></td><td>Life Cycle Carbon tool only</td><td></td></tr>
<tr><td>B2</td><td>Maintenance</td><td>Reported</td><td>Life Cycle Carbon tool only</td><td rowspan="4">Combined (B2–B5)</td></tr>
<tr><td>B3</td><td>Repair</td><td></td><td>Reported</td></tr>
<tr><td>B4</td><td>Replacement</td><td>Reported</td><td rowspan="2">Combined (B4–B5)</td></tr>
<tr><td>B5</td><td>Refurbishment</td><td></td></tr>
<tr><td>B6</td><td>Operational energy use</td><td>Optional (user input)</td><td>Life Cycle Carbon tool only</td><td>Optional (user input)</td></tr>
<tr><td>B7</td><td>Operational water use</td><td></td><td>Life Cycle Carbon tool only (optional)</td><td></td></tr>
<tr><td>B8</td><td>User activities</td><td></td><td></td><td></td></tr>
<tr><td>C1</td><td>Deconstruction/demolition</td><td>Reported</td><td>Life Cycle Carbon tool only</td><td></td></tr>
<tr><td>C2</td><td>Transport</td><td>Reported</td><td>Reported</td><td rowspan="3">Combined (C2–C4)</td></tr>
<tr><td>C3</td><td>Waste processing</td><td rowspan="2">Combined (C3–C4)</td><td>Reported</td></tr>
<tr><td>C4</td><td>Disposal</td><td>Reported</td></tr>
<tr><td>D1</td><td>Net flows from reuse, recycling, energy recovery</td><td>Reported</td><td>Life Cycle Carbon tool only</td><td>Reported</td></tr>
<tr><td>D2</td><td>Exported utilities</td><td></td><td></td><td></td></tr>
</table>

*Includes construction operations impacts for some materials only, such as estimates for energy required to operate cranes to lift heavy materials. Also includes production, transport, and EOL impacts of construction-generated waste material.

**One Click LCA provides many tools on its platform. These two tools – LCA for LEED and Life Cycle Carbon - Global – are the most applicable of its tools in North America.

Calculators are typically not appropriate for policy compliance as they do not include enough specific inputs to represent a building; they are intended to help designers make decisions, not report on the actual materials used in a project. One exception is the BEAM Estimator tool, which will be used by the City of Toronto for compliance. The Building Emissions Accounting for Materials (BEAM) tool estimates the cradle-to-gate (A1–3) emissions from low- and mid-rise residential buildings using EPDs, with a focus on incentivizing biogenic carbon storage in building materials.

2.4.4 Key Actors/Organizations

Some key actors in the Building LCA ecosystem include:

- **architects, engineers, and consultants:** who typically perform the WBLCA and provide material assignments, quantity take-offs (if based on BIM and project-level scenarios);
- **contractors:** who may calculate, update, or verify material quantities, construction processes, on-site fuel, energy or water consumption (if included), and A4 transportation distances based on materials procured;
- **building owner:** who may pay for the LCA (directly or indirectly) and may drive the goal and scope of the LCA (e.g.,

green building certification goals, emissions accounting). Some building owners may conduct their own building LCAs to establish project baselines, or to include in a larger portfolio-wide measurement and reporting effort;

- **agencies and code officials:** who, as WBLCA is integrated into building code, will be key actors in collecting, reviewing, and verifying WBLCA results, in a manner similar to building energy models for energy code compliance;
- **NGOs and academics:** who collect and publish project LCA results to establish benchmarks.

When the whole-life carbon (also known as total carbon) of a building is reported, rather than reporting the embodied and operational carbon separately, there are additional key actors, such as energy modelers and systems engineers. These may or may not be the same individuals or organizations collecting data on building materials and performing the building LCA.

Mapping the Building LCA Ecosystem

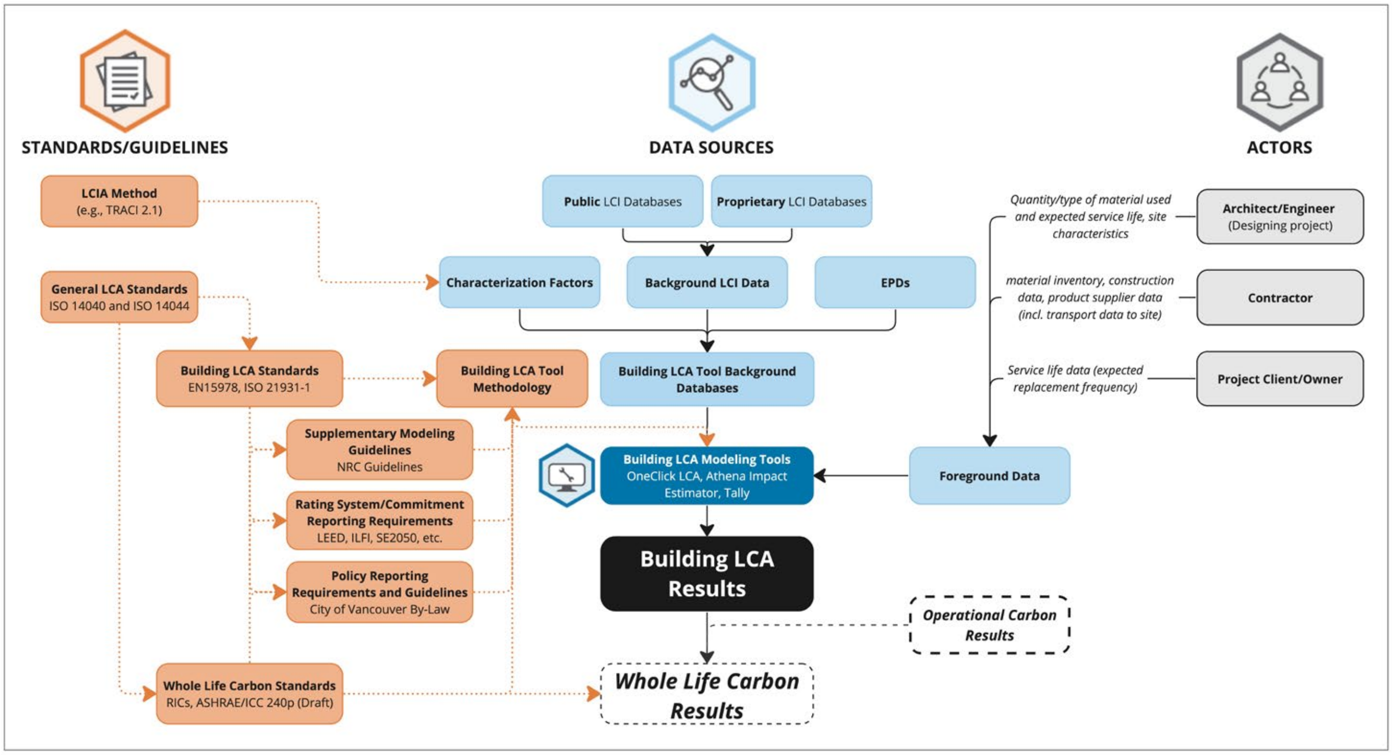

Figure 8. Mapping the building LCA ecosystem.

2.5 Project LCA Ecosystem – Infrastructure

Infrastructure is a broad sector with many unique project types. At the present time we recommend beginning with pavement LCA and then expanding to roadway LCA and later other types of infrastructure LCA, given the significance of pavement and roadways in terms of total emissions impact and ubiquitous application. In the context of policy, this section generally applies to projects completed by national, state, and local transportation agencies. This report uses "roadway LCA" to include road elements (pavement and sub-layers), sidewalks, medians, curbs, bridges, etc. While "roadway" does not necessarily cover all horizontal/civil infrastructure, this section doesn't necessarily mean to be limiting – tunnels, railroad tracks, etc. could potentially be included in a broader civil infrastructure LCA ecosystem.

Many aspects of roadways and roadway LCA mirror the discussion of buildings and WBLCA above, and thus their LCA ecosystems overlap significantly. For example, both involve combining multiple products and processes to create a project; site work (e.g., excavation); same or similar data and methods related to concrete and steel reinforcement; embodied impacts and operational impacts (though in both cases, different studies focus more or less on either of these impact types); maintenance and replacement as significant contributors to lifetime GWP.

There are some key differences to the LCA ecosystems between the two. Asphalt mixtures are unique to roadways. (There are some asphalt-related building products, such as for some roofing materials, but not the asphalt mixtures we see on most roadways.) While buildings and roadways each can have significant quantities of concrete, mixes may have roadway-specific performance characteristics (e.g., more admixtures to help concrete mix cure and set faster, or very tough mixes with low slump). For roadways, operational impacts are about vehicle emissions (not people or mechanical, electrical, plumbing (MEP) equipment emissions, etc.). For example, different pavements have different roughness or smoothness properties, which affect the efficiency of vehicles driving on them. So pavement type indirectly affects vehicle-fuel-consumption emissions. (This is loosely analogous to a building's envelope assembly's indirect effects on energy demands for heating and cooling a building.)

2.5.1 Roadway LCA Standards

Many of the above-described standards apply to roadway LCA, particularly ISO 14040, ISO 14044, ISO 21930, and EN 15804. The following documents are specific to the roadway LCA ecosystem.

- ***ISO 21931-2:2019 Sustainability in buildings and civil engineering works — Framework for methods of assessment of the environmental, social and economic performance of construction works as a basis for sustainability assessment — Part 2: Civil engineering works*** provides the framework and methods for LCA (and other sustainability performance assessments) of roadways and other civil engineering works. In light of various (non-harmonized) existing sustainability assessment programs, this standard "aims to bridge the gap betweeay projen regional and national methods for the assessment of the sustainability performance of civil engineering works by providing a common framework for their expression" (ISO, 2019). The standard helps define the scope of a roadway LCA assessment – which can be the whole roadwct ("civil engineering works" in the standard's language), a part of the project, or a combination of several projects. The scope can also include use of the project (not just the initial construction), including transportation impacts of the project users. Note that while this standard exists, it is not frequently referenced.

North American guidance documents

- The **Federal Highway Administration's (FHWA)** ***Pavement Life Cycle Assessment Framework*** outlines the need for such a framework and the uses of pavement LCA (alignment around assessment methods to support LCA-based decision-making for pavements). It is explicitly NOT a standard but rather a guidance document that "provides a general framework for conducting LCA studies on pavement materials, projects and systems, describing the current status of the LCA methodology and its application to pavements. Importantly, this document provides guidance for agencies, but also allows for the description of viable alternatives (and their pros and cons) where they exist, as well as the documentation of current practices and experiences" (FHWA, 2016).

2.5.2 Roadway LCA Data Sources

Foreground data for roadway LCA

Many foreground data sources for roadway LCA are very similar to those for WBLCA:

- quantity and type for each material or assembly used (e.g., tons of gravel)
- site characteristics
- transportation data: vehicles used and distance traveled to transport materials to site
  - Note: Hauling fill and other site materials can be a significant portion of roadway construction impact, especially for new construction that involves large quantities of cut and fill material.
- construction data on site electricity use, water use, equipment and fuel usage, and construction waste (if collected)
- service life data for products, as indicated by manufacturer
- EOL scenarios.

Other sources for foreground data are pavement smoothness/roughness information and work zone information related to potential traffic disruptions.

Background data for roadway LCA

Background data sources specific to roadway LCA include:

- the Asphalt Institute's "LCA of Asphalt Binder" containing LCI data available in the Federal LCA Commons
- CA4PRS for work zone traffic modeling
- operational-energy-related pavement roughness prediction models
- pavement LCA tool background databases: assembly/material data, construction waste factors, EOL models, service life assumptions, other construction/use scenarios, material LCI data
- EPDs: product-specific or IW-EPDs may be used as data sources for products in project LCA. Note that the appropriate use of EPDs as data sources requires a degree of harmonization across PCRs and roadway LCA methodology, as outlined in the ACLCA's PCR Open Standard and described elsewhere in this report.

The same background data sources listed in Section 2.2.2 also apply to roadways.

2.5.3 Roadway LCA Tools

In addition to the primary LCA modeling tools mentioned above that can be used by experienced LCA practitioners (openLCA, SimaPro, GaBi), the following tools are specific to pavements and roadways:

- FHWA's LCA Pave tool: a free spreadsheet-based pavement LCA tool for both asphalt- and concrete-based pavements
- Athena's Pavement LCA tool: a free software for LCA of U.S. and Canadian roadway designs
- University of California Davis's eLCAP: a tool focused on operational energy consumption from pavement–vehicle interaction (relevant for module B6 for pavement LCA)
- the Pavement Life-cycle Assessment Tool for Environmental and Economic Effects (PaLATE): a spreadsheet LCA and life cycle cost analysis developed by a University of California Berkeley program and focusing on pavement and road construction, addressing both environmental impacts and costs.

2.5.4 Key Actors/Organizations

Some key actors in the roadway LCA ecosystem include:

- **engineers, consultants, NGOs, and academics**: who perform roadway LCAs;
- **contractors and engineers:** who provide material quantity data, performance characteristics, and (if available) construction data;
- **transportation agencies:** which are typically responsible for funding roadway projects and therefore the LCA (directly or indirectly).

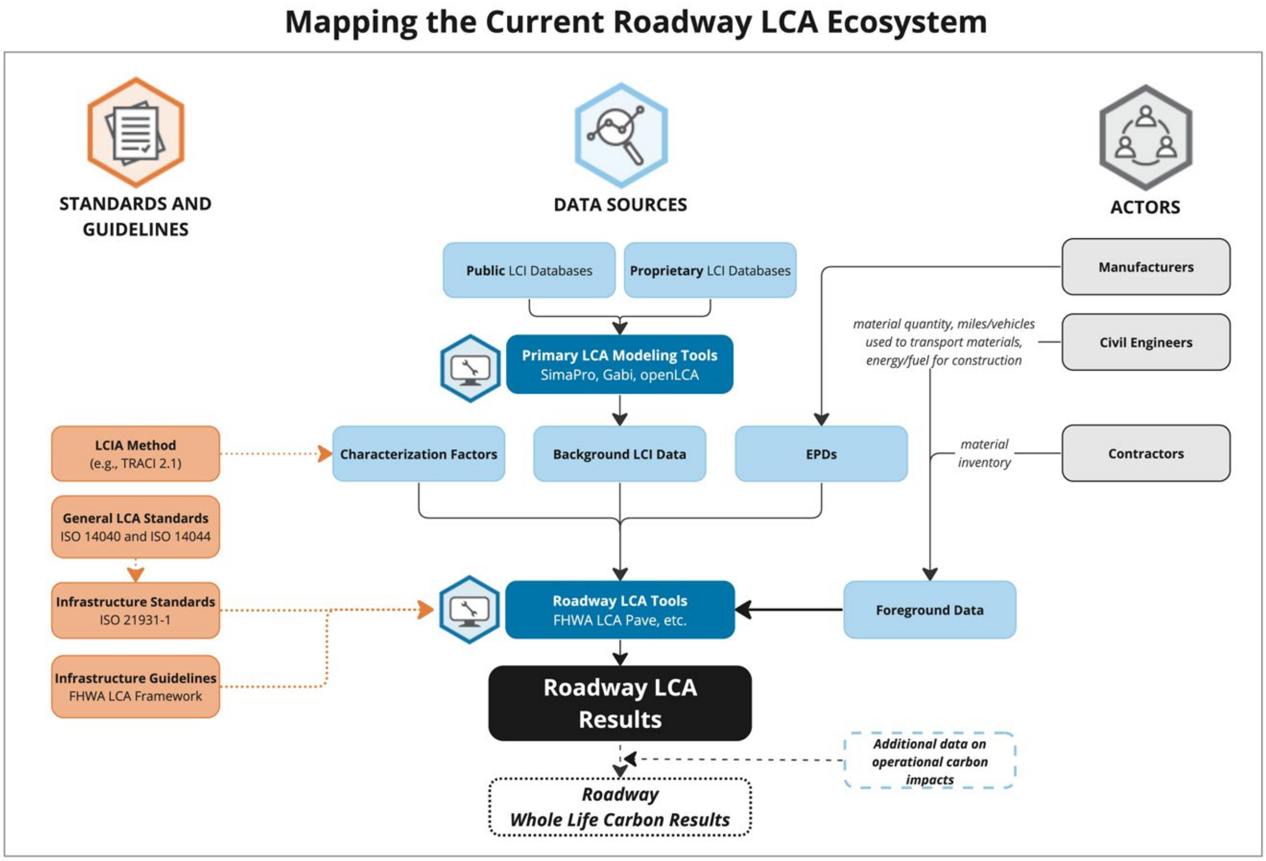

Figure 9. Mapping the current roadway LCA ecosystem.

3. A ROADMAP: CHALLENGES AND PROPOSED SOLUTIONS

The effectiveness of policies that use LCA as a reporting tool relies on the strength of standards to provide a framework for consistent LCA results across assessments, on the availability of quality accessible background data, and on the tools that are used to access that data and evaluate products and projects. These three building blocks – standards, data, and tools – along with the people and organizations engaged in all aspects of this ecosystem will support the generation of reliable and comparable LCA results that policies will require.

An "ideal" LCA ecosystem optimized for policy would be:

- **open and transparent** through shifting the balance from proprietary data and models to open, high-quality data in public repositories and investing in open data infrastructure;
- **accessible** through expanded access to training, streamlined processes and tools for reporting, and financial support for those who really need it;
- **more comparable and reliable**, with differences in LCA results reflecting differences in the carbon footprints of products or projects, not differences in the data, tools, and methodologies used by practitioners;
- **globally harmonized** to streamline the use of LCA data and tools across regional and international borders, particularly for globally traded materials, and across sectors (e.g., products and projects);
- **able to keep pace with new materials, technologies, and processes** to better track and support decarbonization and to fill the gaps in current standards, data, and tools by exploring and measuring those new materials, technologies, and processes.

This section highlights current needs for strengthening the current LCA ecosystem, what gaps need to be filled, and a list of solutions for advancing progress toward the ideal ecosystem described above.

3.1 Advancing Foundational LCA for Policy

Improving the foundational LCA ecosystem is critical to improving LCA-based policies across sectors and project types, as these standards, datasets, and tools impact all types of LCA. The following six steps would ensure widespread access to high-quality LCI/LCA data and models, created using updated standards, for use in driving decarbonization through policy.

1. Increase access to high-quality, up-to-date, public LCA datasets and models as consistent sources for background data.

Access to public background LCI data is a critical step toward consistent product and project LCAs. Until recently, the use of LCA has primarily been voluntary, for the purposes of internal or academic research, marketing, or green labeling. Reliance on proprietary databases was acceptable in this landscape, but free, transparent databases and tools are now needed to provide a foundation for disclosure, incentives, and regulatory compliance.

Current challenges include:

- Publicly available and transparent LCI data and tools are limited by available funding and staffing. This has historically resulted in outdated data compared to proprietary counterparts.
- Gaps in LCI data may prevent inclusion of certain products and technologies in policies due to a lack of data with which to assess and report their impacts.
- Different assessments use different background datasets to represent the same processes and materials. Presently, LCA practitioners have a lot of latitude to choose background datasets that alter their model results and limit comparability between assessments.

Addressing these challenges requires a public repository for transparent, freely available LCA data and process models. In North America, this requires **continued development of the U.S. Federal LCA Commons and the Canadian public LCI datasets**. This will require dedicated funding and staffing for many years to come, as well as a multi-agency coordinated plan to fill gaps in the LCA Commons and provide better integration.

Once available, PCRs, building LCA standards, and roadway LCA standards can require these public datasets to increase consistency and reliability across assessments. As public datasets expand and improve, standards can require data for other common construction material inputs to come from these repositories.

As a starting point, public repositories should be referenced by standards and tools for common processes and flows. For example, U.S. public datasets for electricity (U.S. Electricity Baseline developed by EPA and NETL), fuels (USLCI), transportation (USLCI), heavy equipment operation (EPA), and CDD EOL management (EPA) are already available. A next step will be expanding and updating public datasets to cover the manufacturing of common construction materials and processes.

Public datasets must be transparent, regularly updated, and freely available if they are to be required by standards consistently across product and project LCAs.

2. Improve LCA standards to provide more detail and consistency.

Differences in results should be reliably based on differences in the actual product or project, not due to underlying modeling or background data choices. Currently, the following challenges are preventing consistent achievement of that goal:

- The LCIA method used in North America, TRACI, was developed in 2003 and has not been significantly updated since 2011. TRACI 2.1 uses outdated GWP-100 values that are not aligned with the most recent IPCC climate factors and does not separately track biogenic and fossil carbon. Other LCIA methods and data sources (e.g., EN15804, CML, ReCiPe) are updated to more recent IPCC reports and track subsets of GWP (e.g., GWP-total, GWP-fossil, GWP-biogenic, GWP-luluc).
- ISO standards are too vague and require more prescriptive guidance to result in consistent assessments on many topics. There are also conflicts between standards within and across regions, such as the conflicts between ISO 21930 and EN15804 described in Section 2.3.1.
- Uncertainty/variability methods are not aligned or applied across tools and methods.
- Modeling and reporting of biogenic carbon accounting (including the treatment of CO_2 sequestered during plant growth, the carbon stored in ecosystem stocks such as soils, and carbon stored in building materials) vary widely. This makes it difficult or impossible to fairly compare some materials, and industry interests (on both sides) are currently preventing progress.
- LCA methods may vary between assessments and datasets for service life assumptions (B stage); EOL assumptions (C stage); and allocation method (e.g., dividing emissions between more than one interconnected product system), and assumptions and methods around reuse, recovery, and recycling (D stage).

Addressing these challenges requires improvement of existing standards (ISO and TRACI) and creation of new standards to address biogenic carbon accounting and carbon storage.

First, the most broadly used North American LCIA method, TRACI 2.1, impacts all North American LCA results and must be updated to (1) align GWP characterization factors with the most recent IPCC assessment report and (2) distinguish between biogenic and fossil carbon flows, as is already done by European LCIA methods (e.g., GWP-total, GWP-fossil, GWP-biogenic, GWP-luluc).

Policymakers must advocate for dedicated funding for future updates to TRACI 2.1 to keep pace with updates to the IPCC, or international harmonization will continue to be difficult or impossible.

Existing ISO standards can be updated to provide more prescriptive guidance to increase consistency across assessments and to address conflicts with EN standards where possible. More prescriptive guidance is required for compiling LCI data, modeling protocols, and applying uncertainty/variability analyses. Regional and/or user-specific guidance documents can also play a key role in bridging the gap between the flexibility of international standards and practitioner/policy needs for more prescriptive guidance to increase consistency and standardization. Governments and nongovernmental bodies with broad influence should support adoption of this type of guidance document to increase use.

A new consensus standard is required for consistency across LCA modeling for evaluating the GWP benefits of biogenic carbon and accounting for delayed storage. Standardizing a science-based approach to these topics across tools and assessments will greatly increase consistency of results, and better capture actual carbon impacts and reductions.

3. Provide more LCA training and credential opportunities.

LCA is complex. Policies requiring LCA results will require more LCA and building industry practitioners to be trained to perform LCAs. Policymakers also need enough knowledge to incorporate EPD and project LCA results effectively into policies and to advocate for the government agency funding required to strengthen the LCA ecosystem.

To address this challenge, universities and professional training program providers need to expand opportunities for students to choose careers as LCA practitioners and for professionals to train in LCA. More basic training should be freely available and tailored to policymakers.

Existing credential programs, such as the ACLCA's Life Cycle Assessment Certified Professional (LCACP) certification, help create a community of practice and opportunities for LCA practitioners to engage with other practitioners and ensure they are implementing best practices through continuing education. This program is for LCA professionals with advanced degrees and experience in LCA, similar to a licensing program with continuing education requirements for architects or engineers. Expanding the community of LCA practitioners may require additional opportunities for those transitioning careers.

4. Fill gaps in available LCI data to increase the accuracy of LCA results.

Currently, there are two types of LCI data gap limiting the accuracy of models and results. First, there are complete gaps in LCI data for some types of product or process, such as alternative materials and new technologies that are being developed specifically with goals of decarbonization. Second, there are products or processes where LCI data is available but there is no technologically or regionally specific data available to improve the accuracy of assessments. This is similar for scenario development for use and EOL phases. This data is available, but industry has not yet released it in a way that can be used to create this data source.

Discussions of background data specificity often focus on each end of the spectrum – very specific (facility-specific data from the actual supplier of an upstream product) and generic (industry-average data for, e.g., all of North America). However, geography- and/or technology-specific data would enable a meaningful leap in data accuracy between these two extremes: an LCA practitioner might not have access to a supply-chain-specific EPD, but they could choose a more geography- and/or technology-specific data point if one were available (e.g., "CMU from southeastern USA made with Portland limestone cement," rather than "CMU, North America").

Both of these challenges can be addressed by federal agencies working to publish public data, but they will require funding to (1) expand the USLCI to include alternative materials and technologies, and (2) create new tools that help industry report LCA data confidentially to enable agencies to develop publicly available background datasets that are more technology- and/or region-specific than the current available data.

Additionally, public funding could advance research to build up data for service life (for use stage impacts) and EOL scenarios. Service life data could inform standardized values based on the actual, typical service life for materials and products. Expanding the EPA's CDD management data repository to include regional data for the typical EOL fate of common materials and products could increase confidence in stage C results.

5. Improve the interoperability between LCI and LCA datasets and tools.

Datasets and data repositories should adopt and align to a consistent ontology (organizational structure of LCI and LCA data elements and their relationships) and nomenclature (naming, especially of elementary flows). This will enable seamless transitions between datasets and tools.

Currently, LCI data comes from different sources all over the world with different formats, units, organization ("ontology"), and naming ("nomenclature"). This limits the use of global datasets and makes conversions and incorporation of datasets into tools difficult and/or unlikely. This challenge may seem abstract, but it currently prevents the use of some datasets or significantly increases the amount of time required to use them. This discourages an LCA practitioner from, for example, using the most regionally or technologically specific data available, if it requires too much additional time (or isn't possible) to adapt this dataset to use with the rest of their LCA model.

To address this challenge, North American LCI and LCA datasets should leverage ongoing international efforts to adopt a central nomenclature. The U.S. FEDEFL, a part of the LCA Commons, can adopt the UN Environment Programme's (UNEP) GLAM (Global Guidance for Life Cycle Impact Assessment Indicators and Methods) initiative's central nomenclature for elementary flows. All U.S. public datasets can reference the FEDEFL, so only one list would require updates in the future as needed. The UNEP also has related initiatives to increase LCI-LCIA interoperability (GLAM) and support converting between data formats (GLAD – "Global LCA Data Access" network).

6. Explore opportunities to use LCA to address policy priorities beyond carbon.

Human and environmental health impacts from products and projects go far beyond GHG emissions. The human health impacts from the full life cycle of construction materials and projects contribute to negative health impacts, such as exposure to fine particulate matter ($PM_{2.5}$), that are significant and often ignored (Greer et al, 2022).

LCA can also be used to track the local, regional, and global environmental impacts beyond GWP. Smog formation potential, acidification potential, eutrophication potential, and other life-cycle impact results may offer opportunities for policy to track progress across a broader set of climate, environmental,

Table 5. Summary table of six steps for advancing the foundational LCA ecosystem for policy.

Solution	Specific recommendations
1. Increase access to high-quality, up-to-date, public LCA datasets and models as consistent sources for background data.	• Provide dedicated staffing and funding across agencies to maintain and update the Federal LCA Commons and the Canadian public LCI datasets. • Create a multi-agency coordinated plan to fill gaps in the LCA Commons and provide better integration/interoperability between datasets. • Update public datasets (e.g., Federal LCA Commons) to serve as consistent data sources for common processes and flows (electricity, fuels, transportation, heavy equipment operation, etc.). • Expand and update public LCI databases to cover manufacturing of common construction materials.
2. Improve LCA standards to provide more detail and consistency.	• Update TRACI 2.1 to refer to more recent IPCC factors for GWP and to distinguish between biogenic and fossil carbon flows. Dedicate funding for future updates as IPCC continues to update. • Update ISO standards to support harmonization with EN standards and provide more prescriptive guidance on compiling LCI data and LCA modeling protocols. • Update or build on ISO to better evaluate the GWP benefits of carbon storage, including delayed biogenic carbon emissions accounting and avoiding double-counting of carbon storage credit.
3. Provide more LCA training and credential opportunities.	• Increase the availability of LCA training and university programs for LCA practitioners, designers (architects, engineers), and builders. • Support the ACLCA Credential Program or similar to support the LCA community and increase practitioner consistency.
4. Fill gaps in available data to increase the accuracy of LCA results.	• Expand the public LCI databases to fill gaps relating to alternative materials, technologies, and processes.. • Create user-friendly tools for confidential LCA data disclosure for industry. • Use industry-reported data to create technology- and region-specific background data based on aggregated confidential data as part of the Federal LCA Commons repositories. • Improve accuracy of service life data for materials and products. • Expand the EPA's CDD management data repository to include regional typical EOL fates for common materials.
5. Improve the interoperability between LCI and LCA datasets and tools.	• Leverage the UNEP GLAM initiative to adopt a harmonized central nomenclature list for elementary flows for the FEDEFL. Update public data repositories to adopt the FEDEFL. • Leverage GLAM's work on LCI-LCIA interoperability, so that LCI datasets operate with TRACI and LCIA results account for all items in the inventory. • Leverage existing programs that convert between data formats, such as GreenDelta's openLCA conversion service used by the UNEP's GLAD initiative.
6. Explore opportunities to use LCA to address policy priorities beyond carbon.	• Lead research and consensus-building among LCA experts to identify which impacts outside of carbon (e.g., smog formation, eutrophication, etc.) are appropriate and ready for policy use and develop pathways to overcome existing limitations to use.

and environmental justice policy priorities. For example, smog formation potential is a local impact expressed in kilograms of ozone equivalent (kgO3e) or kilograms of nitric oxide and nitrogen dioxide (kg NOxe) that can be used to track health impacts from the life cycle of construction materials and projects, many of which fall disproportionately on fenceline communities (Escott et al., 2022).

Currently, the methodology, sources, and units for characterization factors outside of GWP are less widely agreed upon by LCA experts. Additional research and consensus-building is required to establish which impacts are appropriate and ready for policy use, and to develop pathways for implementation.

3.2 Advancing Product LCA and EPDs for Policy

To support effective product-level embodied carbon policies, the LCA ecosystem needs to support EPDs that are:

- reliable (reasonably matched with reality in a way that is consistent with other EPDs);
- comparable (for functionally equivalent products and based on LCAs that use appropriate background data and standardized methods);
- transparent in their specificity and source of data;
- useful as data sources;
- readily available and plentiful;
- accessible (digitized, useful databases for storing and filtering); and
- user-friendly (able to be easily sorted/filtered digitally, with clear terminology and metrics).

The following near- and long-term solutions are about advancing the LCA ecosystem to support the production and use of EPDs that meet these criteria.

1. Continue to increase EPD availability and accessibility.

While there has been significant growth of EPDs in the last few years, the current availability of product EPDs still varies significantly by state and product due to a lack of motivation, knowledge, or resources for creating EPDs.

Manufacturers and industry associations for product types included in Buy Clean and similar policies argue that unequal inclusion of product types has placed an inequitable burden on their industry. Policymakers currently face a choice between focusing on fairness between different competing materials (e.g., if one structural material is included, then all should be) versus focusing on ease of compliance by starting with a shorter list of materials with more current data. Increasing EPD availability across all product types will enable policymakers to choose which products to include in policies based on carbon intensity, perceived fairness, or other policy priorities, rather than being influenced by data availability.

To achieve the critical mass of EPDs for effective EPD-based policies, manufacturers must be motivated to produce EPDs and able to develop and easily update EPDs in a streamlined, cost-effective manner. Solutions include:

- **Requiring EPD disclosure in public and private sector policy** to send a demand signal across the industry, such as through Buy Clean and similar government procurement policies or through building codes. These policies are already underway across much of the United States for public sector projects through state and federal policy and are increasing on private sector projects.

- **Providing financial or technical assistance for manufacturers** for EPD development or updates and third-party verification. Incentives could target small-to-midsize companies that lack dedicated resources for EPD production and regions or product types that lack data, such as MEP equipment and novel materials. The EPA's Inflation Reduction Act funding (section 60112) for EPD assistance for construction materials will hopefully address this need in the United States.
- **Make EPD production cheaper, faster, and more consistent** by increasing access to EPD generator tools that streamline EPD production for manufacturers. See more in Solution 4 below.

While general knowledge of EPDs has increased significantly in the past decade, **more widespread education on EPDs** is still needed to support the increase and use of available EPDs. Government agencies need to understand EPDs well enough to manage procurement programs that require EPD disclosure, and contractors have a particularly key role in following through on EPD requirements in the procurement process through collecting and reviewing EPDs and communicating with suppliers. Providing training for government agencies and contractors, before or alongside policy requirements, will support effective use of EPDs in procurement.

Last, **widespread adoption of digital EPD formats** is needed for EPDs to be accessible and useful for end-users. Digitized EPDs are easily sortable and filterable (based on numerous parameters depending on product type) and can be accurately and efficiently housed in EPD databases for end-users to set threshold GWP values and procure products in compliance with thresholds. EPD databases such as Building Transparency's EC3 aim to address these issues, but currently need to run scripts to translate non-machine-readable PDFs into a digitized format in order to incorporate the EPD data into the database, a process that is hampered by errors and omissions due to interoperability issues and non standardized data fields.

The open-source openEPD digital EPD format addresses these challenges and has already been adopted by some program operators and EPD producers (such as Climate Earth, SmartEPD, and WAP Sustainability). However, broader adoption is still needed to ensure EPD accessibility. European EPDs may also use the ILCD+EPD digital format. Notably, EPDs using the openEPD digital format are compliant with the ILCD+EPD format, but not vice versa. Therefore, we recommend broad adoption of the openEPD format to maximize interoperability.

2. Strengthen PCRs and the PCR development processes for EPD reliability and comparability.

EPD reliability and comparability are heavily dependent on the PCRs that provide the rules and frameworks for creating those EPDs. Therefore, improving PCRs – both the process by which they are created and their content, which directly influences EPD content – is the most important lever for increasing EPD reliability and comparability for policy.

PCR development is currently hindered by a lack of funding, a lack of centralized oversight, and conflicts of interest on the committees. Program operators are not paid very much to develop PCRs, and payment is usually by a single trade association that has outsized influence on who is invited to the PCR committee. No overarching authority oversees or harmonizes PCR efforts across or within program operators, and ISO standards provide significant flexibility to program operators, resulting in inconsistencies across PCRs (Rangelov et al., 2021; Subramanian, 2012; U.S. EPA, 2023). While some flexibility is necessary for addressing nuances between different products, PCRs currently vary in aspects that are important for providing transparency and comparability, as they are developed only to best reflect the interests of the represented industry.

Improving PCRs therefore begins with strengthening the PCR development process, including by:

- **providing funding support for PCR development,** which is particularly important for the development of new PCRs, material-agnostic PCRs, and PCRs for product categories that do not have large well-resourced trade associations;
- **increasing and diversifying stakeholder engagement on PCR committees** to reduce conflicts of interest and represent a range of both EPD producer *and* end-user perspectives. Financial and technical support for public agency, NGO, or practitioner participation in PCR committees would make this more feasible, as currently large manufacturers are often the only stakeholders with capacity to participate;
- **strengthening the requirements that program operators must follow when developing and updating PCRs**, by implementing national or North American PCR requirements such as described in Solution 3 below, would increase consistency across PCRs.

A stronger PCR development process will enable the next step in updating PCRs to address current challenges to the quality of individual PCRs, such as the varying data and LCA method requirements allowed, the varying levels of uncertainty reporting, and PCR scope.

PCRs vary in terms of how prescriptive they are regarding which background data sources they allow in EPDs. Thus, in some cases, EPDs following the same PCR may use different background data to model the same physical process or material. For example: two different manufacturers located across the street from each other make the same product using similar manufacturing processes that consume similar (yet significant) amounts of electricity. If the PCR isn't explicit about which electricity factors to use, the LCA practitioner has the choice of selecting utility, state, or regional grid emission factors. If each manufacturer picks a different factor, the difference between their reported product emissions could be significant even though the actual difference between the product emissions is negligible.

EPDs also typically declare a single deterministic GWP value (i.e., a point value and not a range), despite the high variability and uncertainty behind that value, due to factors like the quality or representativeness of the LCI data, the quality of the primary data collection, and differences in modeling (Bhat, 2020; DeRoussea et al., 2022; Rangelov et al., 2021; AzariJafari et al., 2023). Some tools and programs incorporate uncertainty and variability in EPD reporting and some do not.

Existing PCRs often don't align with each other in terms of scope, LCA methods, and definitions, such as which life-cycle stages are included, which LCIA factors are used, allocation methods, and how to define facility-specific or other more recent EPD terms. This means that EPDs within the same PCR may be comparable, but this non-alignment limits the combination of different product type EPDs as data sources for building or infrastructure LCAs since the results are not comparable across PCRs.

Last, some decarbonization strategies used by manufacturers are not captured in EPDs yet, due to a lack of data or a lack of consensus on a robust methodology for calculating these carbon benefits without double-counting. A few examples include carbon capture and storage, bio-based products that store biogenic carbon, and virtual power purchasing agreements for renewable energy. In some cases, this is because of a lack of broader consensus, like on the topic of accounting for the benefits of carbon storage, but in other cases PCRs may need to expand to enable newer materials or technologies to be included.

As new PCRs are developed and existing ones are updated, PCRs can update to adopt best practices for improving and harmonizing PCRs, including by:

- **prescribing publicly available background data sources, beginning with universal flows.** One of the most significant steps a PCR can do to improve EPD comparability is to be more prescriptive regarding background data sources. For universal flows (e.g., electricity, fuels, etc.), PCRs should require consistent use of publicly available LCI data, whenever possible. For upstream materials and processes where supply-chain-specific data is not required or available, PCRs can prescribe a generic/industry-average secondary data source and report the uncertainty associated with this data. This requires building up public background datasets, as described in the first solution in 3.1 above;
- **requiring standardized reporting of EPD specificity** (e.g., "This EPD is product-specific, facility-specific, manufacturer-specific; 30% of the contribution to GWP is from supply-chain-specific data.") and defining product-specific, facility-specific, and manufacturer-specific calculations. This is already built into the openEPD digital format and the EC3 tool, but requires adoption of consistent definitions across PCRs for implementation. The ACLCA is also currently working on a "Types of EPDs" addendum to its PCR Guidance that aims to address this issue by providing standardized terminology and reporting guidance;
- **requiring facility-specific foreground data**, as is already required by many Buy Clean policies. Operations within the direct scope of the manufacturer producing the EPD (typically accounted for in A3) should be reported by facility, rather than averaging across multiple facilities. This data is already collected separately, so facility-specific reporting should not present a cost or time burden;
- **requiring specific data for upstream processes that contribute significantly to total emissions**. The first option to achieve this would be to agree on a reporting threshold for what threshold determines significant contribution. For example, Kardish (2023) suggests 80% of total cradle-to-gate emissions; the ACLCA Open Standard states "upstream unit processes that cumulatively contribute 50% or more to the disclosed [GWP]" (ACLCA, 2022); and others have suggested that any given single upstream process that contributes at least 20% to total

GWP ought to use supply-chain-specific data (CLF et al. RFI response, 2023). The second option would be to require a cumulative % specificity threshold instead that relates to specific data across life-cycle stages (i.e., at the manufacturer's facility as well as upstream). This could reduce the complexity of setting requirements that relate to many different product types, if specificity reporting is done consistently;

- **requiring reporting of uncertainty for a given EPD result**, based on a consistent and agreed-upon methodology for calculating uncertainty. For example, a method could describe how to aggregate uncertainty subfactors for individual materials and processes in an LCA model, where each subfactor is based on (i) specificity of the data used to represent the material/process, (ii) variability in the market for that material/process, and (iii) contribution to total reported GWP (DeRoussea et al., 2022). This value should be reported transparently on top of EPD results, so policies and programs can choose how to use this data in benchmarking;
- **tying EPD validity to PCR validity**, as is already required by the asphalt mixture PCR. For most categories, EPDs are valid for five years and are not required to be updated when the PCR is updated, causing comparability problems between EPDs from different PCRs (i.e., one new PCR and one old, expired PCR) (Rangelov et al., 2021);
- **requiring adoption of digital EPD formats** for more EPD accessibility and utility (e.g. openEPD). Standardized data fields allow for interoperability between tools and databases and efficient and reliable incorporation into databases. This allows users to more easily and reliably search, sort, filter, and analyze EPD data to use on their projects;
- **expanding the required life-cycle scope to cradle-to-grave or cradle-to-cradle, where appropriate**, such as for product types where downstream impacts relate to the specific product (i.e., variations exist within a product category). Examples would be where products that use the same PCR have different replacement rates, or may use different use-phase and EOL foam-blowing-agent emissions;
- **standardizing and improving reporting of product performance characteristics in EPDs to improve comparability**. The more that product performance data is reported in a substantive and consistent way, the more straightforward it will be to facilitate appropriate apples-to-apples comparisons (and reduce accidental inappropriate comparisons of non-functionally-equivalent products). For example, insulation EPDs use a functional unit that incorporates R-value. This is critical for comparability, as thermal resistance is the most significant performance characteristic of insulation products. However, there are many other physical and performance attributes of insulation products (related to, e.g., moisture resistance, compressive strength, fire resistance, etc.) that affect a product's function in the building application, and thus affect EPD comparability. Standardized reporting for those attributes would facilitate comparability;
- **developing material-agnostic PCRs where appropriate.** Some PCRs could be updated or combined to be ***material agnostic*** – based on function (e.g., cladding) rather than on a specific material (e.g., steel). Current examples of material-agnostic PCRs include flooring, building envelope thermal insulation, and cladding. This is appropriate where the functional unit and the accompanying technical and performance characteristics provide the means to account for functional equivalency of products across material types (e.g., vinyl vs. rubber vs. cork flooring, or mineral wool vs. fiberglass vs. cellulose loose-fill insulation). Some PCRs have already adopted this approach. Material-agnostic PCRs are particularly important for categories where novel alternatives to traditional materials have been developed, so that lower-carbon materials can compete with their functionally equivalent counterparts.

Last, some end-users also still lack confidence in EPD results, regardless of the quality of the underlying PCR. In addition to education and training, **strengthening the verification process** would build confidence in EPDs as mechanisms for policy disclosure. Requiring an accreditation program requirement for EPD verifiers, like the ACLCA's Certified Lifecycle Assessment Reviewer (CLAR) certification, could improve the consistency and quality of verification. More widespread use of EPD generator tools and template LCA models consistent with updated PCRs, as described further in Solution 4 below, would also strengthen the verification process.

3. Create or adopt North American PCR harmonization requirements.

EPDs will not be suitable as data sources for other accounting efforts (e.g., building LCA, roadway LCA, carbon accounting) without harmonization *across* PCRs (ACLCA, 2023; Rangelov et al., 2021; Subramanian, 2012). Additionally, standards for the creation of EPDs vary by country, but products are traded internationally and manufacturers, contractors, and developers have projects across the world. Increasing global alignment across PCRs would enable comparison of products from different countries without requiring global manufacturers to produce multiple EPDs for the same product, as is now the case for manufacturers that must create North American EPDs that conform to ISO 21930 and European EPDs that conform to EN 15804 for the same product.

Harmonized PCRs would:

- prescribe the same background data for universal flows and for materials and processes that affect multiple PCRs;
- use the same LCA methods, such as for allocation;
- use the same impact categories and LCIA methods (or require EPDs to publish multiple LCIA results based on different LCIA methods, as many European EPDs currently do in order to conform to both ISO 21930 and EN 15804);
- have the same level of detail and prescriptiveness for different components of the PCR;
- use a common product classification system across regions/countries;
- provide standardized technical terms and guidance on equivalent terms;
- require standardized reporting of EPD specificity;
- establish a standardized approach for overall EPD uncertainty calculations;
- establish a common definition of representativeness in IW-EPDs by providing guidelines for how to define, measure, and report representativeness and variability of the industry in an IW-EPD.

There is a need to harmonize PCRs within North America, as well as between North America and other countries that use non-ISO standards. The UN's IDDI guidance for global harmonization for concrete, cement, and steel PCRs is a first step toward global harmonization of PCRs, beginning with three key industrial materials. Ideally, this type of international collaboration can help advance harmonization across PCRs simultaneously.

Achieving harmonization across PCRs within North America will likely require a top-down approach, as bottom-up/voluntary harmonization efforts have failed to result in harmonized standards today.

A "bottom-up" approach to harmonization would entail EPD program operators voluntarily adopting new or existing guidance that contains the elements described above (sharing a common template, etc.). The ACLCA published updated PCR guidance in 2022 that North American program operators could adopt, as was done with ACLCA's 2013 PCR Guidance. While the 2013 guidance focused on global harmonization and providing more prescriptive guidance as a complement to ISO (ACLCA, 2022; Subramanian, 2012), the 2022 ACLCA PCR Guidance continues this effort and focuses on improving North American PCRs to meet current and future data and policy needs. The Program Operator Consortium in North America could theoretically meet this need for coordination, but lacks widespread engagement among program operators. ECO Platform is a Europe-based umbrella organization for program operators that could provide a useful example to North America.

A "top-down" approach to harmonization across PCRs would require the creation of national or North American PCR harmonization requirements across program operators. While ISO 21930[14] already serves as the "core PCR" for building products, an additional intermediary step (between the international standard and specific category PCRs) could build upon the ISO 21930 framework with more North-America-focused prescriptive requirements. In North America, some program operators have a PCR Part A specific to their own program. Cross-program operator harmonization could potentially come in the form of a unified Part A, but would require additional guidelines to address some of the criteria described above. European nationwide PCR programs provide examples of creating consistency through a top-down process (Rangelov et al., 2021).

Implementing a top-down approach for cross-PCR harmonization could happen in many ways:

- Federal requirements for PCRs could be put in place, with only EPDs that follow them being accepted. For example, the U.S. EPA could require EPDs to use PCRs that adhere to a set of PCR criteria to receive financial assistance through their Inflation Reduction Act assistance program (section 60112 of the Inflation Reduction Act of 2022). These requirements could be set by the EPA or build off of existing work, such as the ACLCA Open Standard described above, and be adopted by state and local regulation and incentive programs as well. This could be presented as a "Part A" PCR for building products or other formats.
- A third-party conformity assessment program for PCRs could identify PCRs that conform to an international or North American PCR harmonization assessment standard. Like EPDs, PCRs undergo an external review process before publication, but the extent and scope of that review is inconsistent. The creation of a more rigorous multi-stakeholder consensus-based PCR standard and

14 In some cases EN 15804 serves as the core standard for North American subcategory PCRs.

third-party conformity assessment program would ensure compliance with a set of requirements across PCRs.

- Voluntary programs, such as the rating systems developed by the U. S. Green Building Council and the International Living Future Institute, could also allow only EPDs that use PCRs aligning with a set of North American PCR requirements, adding to the incentive for program operators and PCR committees to adopt the requirements.

4. Increase access to public EPD generator tools.

EPD generation tools allow companies to more quickly, easily, and cost-effectively produce and update EPDs that are more consistent, easier to verify (Rangelov et al., 2021), and enable practitioners to focus on foreground data collection and processes unique to a product. Ideally, these EPD generation tools should:

- **provide PCR-specific LCI and data collection templates** and template models, ideally already available through the PCR development process;
- **build in prescribed, public background datasets linked to their source to facilitate easy updates. F**or example, when an updated electricity baseline dataset becomes available on the Federal LCA Commons, a connected model makes it easy to update the LCA – and the resulting EPD – that depends on that background electricity data (Feraldi, 2023);
- **allow for two-way integration**. In addition to one-way integration (data moving from a central repository to the EPD producer), manufacturers could share primary collected data anonymously into an ever-growing industry-generated dataset to be used as background data for other studies (Feraldi, 2023) and to contribute directly to IW-EPDs;
- **be transparent and publicly available** to promote access and allow for more "comparable, interoperable, and machine-readable" carbon accounting data (McGrath, 2023). This will require government financial and/or technical support to industry organizations and tool developers for development and integration with government-funded datasets.

5. Increase availability of industry data for setting policy emissions thresholds.

Setting emissions thresholds requires access to representative industry data to calculate current industry embodied carbon distribution (e.g., 20th or 80th percentiles) for functionally equivalent products (Tilak et al., 2022). This industry data typically comes from an IW-EPD, a collection of product EPDs, or both.

Without data on production quantities, it is not possible to understand how the spread of product EPDs used in benchmarking relates to the true breadth of products in the market, meaning that a collection of product EPDs[15] is often insufficient to represent the industry. IW-EPDs cover multiple manufacturers across an industry and are production-weighted, and thus are already often the most appropriate data sources to use to set GWP benchmarks (Waldman et al., 2023). However, not all IW-EPDs are currently transparent about how representative their sample of manufacturers is, and they may report a single average value rather than a production-weighted distribution of data of their industry.

Improving IW-EPDs as a resource for benchmarking is a critical first step in supporting the development of robust policy baselines and targets. This requires:

- existing IW-EPDs being updated to report more data on the **representativeness of the industry** in terms of facility size, technologies, geography, and percent of total North American production captured in the IW-EPD;
- existing IW-EPDs being updated to include **statistical data on the range of impacts,** beyond the typical single average reported GWP result. For example, they could include minimum, maximum, and standard deviation of the production-weighted GWP distribution. Alternatively, they could report quintiles (20th, 40th, 50th (median), 60th, and 80th percentiles). Ideally, this statistical data should account for upstream supply chain variability (e.g., a fabricated steel product IW-EPD's reported range of results should account for variation in steel production, and a ready-mixed concrete IW-EPD's reported range of results should account for variation in cement production);
- **funding and outreach for manufacturers to increase participation in IW-EPD development**. A low percentage of participation among an industry does not necessarily limit the representativeness of an IW-EPD, if the sample represents the distribution of geographic,

15 This report uses the term "product EPD" to mean an EPD representing products produced by one manufacturer, as opposed to an IW-EPD that represents products produced by multiple manufacturers. This is sometimes referred to as "manufacturer-specific EPD" or as "product-specific EPD." Note that this terminology is not used consistently across the industry, and that "product-specific EPD" sometimes refers to a subset of "manufacturer-specific EPD" that has a more narrowly defined range of products represented (which is why this report avoids the term "product-specific." The ACLCA is currently working on an addendum to its PCR Guidance that provides standard terminology for these and related terms.

Table 6. Summary table of five steps for advancing the product LCA ecosystem for policy.

Solution	Specific recommendations
1. Continue to increase EPD availability and accessibility.	• Require EPDs in policies, codes, and private sector requirements. • Provide financial and technical assistance for EPD production and verification. • Provide training to build capacity in government agencies and contractors to use EPDs for decision-making, before or alongside policy requirements. • Encourage widespread adoption of digital EPD formats (e.g., openEPD). • Support public databases of EPD data to increase accessibility and use.
2. Strengthen PCRs and PCR development processes for EPD reliability / comparability.	• Provide funding support to program operators for PCR development. • Increase and diversify stakeholder engagement on PCR committees. • Strengthen requirements for program operators. • Improve individual PCRs to be more detailed and prescriptive (background data prescriptions, standardized specificity requirements and definitions, standardized reporting of uncertainty, etc.). • Develop material-agnostic PCRs where appropriate. • Strengthen the verification process, potentially through requiring an accreditation program.
3. Create or adopt national and/or international PCR harmonization requirements.	• Support the use of EPDs as a data source for projects or other products through harmonizing *across* PCRs through voluntary adoption of requirements across program operators (e.g., IDDI, ACLCA's Open PCR standard) or mandatory PCR harmonization requirements (federal standard, conformity assessment program or similar).
4. Increase access to public EPD generator tools.	• Create and fund publicly available EPD generator tools that allow for two-way integration with public datasets, are aligned with updated PCRs, and provide streamlined EPD development through simple data collection templates for manufacturers.
5. Increase availability of industry data for setting policy emissions thresholds.	• Require standardized reporting of IW-EPD representativeness and statistical measures based on production weighting. • Provide funding and outreach to manufacturers to increase participation in IW-EPD development. • Use industry input to determine appropriate resolution of emissions thresholds subcategories, in terms of product type and geographic specificity.

technological, and other variation unique to that industry. However, higher participation would obviously increase representativeness;

- **new IW-EPDs being published** for categories where they currently do not exist.

In addition to requiring adequate data for setting GWP limits or targets, **policymakers need industry input to establish meaningful *subcategories* for some products.** The primary goal of categorization is to promote appropriate comparison of functionally equivalent products in order to drive down emissions. For example, within the broader material category of steel, Buy Clean California has GWP limits for four types of steel. The hollow structural section limit is 1,710 kgCO2e per metric tonne of structural steel, and the concrete reinforcing steel limit is 890 kgCO2e for one metric tonne of bar. One number limiting both of these categories would be meaningless, as you cannot use hollow structural steel in place of concrete reinforcing steel; they have completely different functions and are manufactured differently.

There are trade-offs between the resolution and the usefulness of product subcategories for comparison. More narrowly defined categories (e.g., plywood sheathing, EPS insulation) are less likely to inadvertently facilitate inappropriate comparisons of (non-functionally-equivalent) products, but may not capture embodied carbon reduction opportunities achieved through appropriate comparisons across similar products (e.g., between competing insulation products). More widely defined categories (e.g., wood sheathing, board insulation) are more likely to inadvertently facilitate inappropriate comparisons between non-functionally-equivalent products, but they would capture bigger reductions between similar (but not identical) products.

There are also trade-offs related to geographical resolution: should emissions thresholds be set for a country, state, or other regional definition? The answer likely depends on the product type, as some product types have geographically small supply chains and others regularly travel across the country or from overseas. Similarly, some product types' GWP varies more by region (due to, e.g., type of aggregate available for ready-mixed concrete, or electrical grid mix) and other product types' GWP varies less by region (e.g., a product type whose main embodied carbon driver is natural gas combustion, for which geography does not affect emissions).

These questions around categorization are important: How many emissions thresholds are appropriate? How many subcategories? What unit is meaningful for comparison? Without substantial input from producers and users of these materials, these questions are difficult to answer.

3.3 Advancing Building LCA for Policy

Effective building-scale embodied carbon policies will require:

- reliable and consistent WBLCA results that are appropriately comparable to each other and to benchmarks set by policy;
- better data and data collection;
- WBLCA benchmarks informed by rigorous analysis of quality data;
- more widespread knowledge and use of building LCA in the design process; and
- a policy framework to measure and push progress that includes a combination of performance (both regulation- and incentive-based) and prescriptive components.

The seven solutions laid out in this section are in roughly sequential order, as later items depend in part on earlier items. Steps 1–3 provide the data foundation for effective policy, and Steps 4–7 provide a framework for policy and other voluntary programs. Le Den et al. (2022) outline a building-scale embodied carbon performance system for Europe, and this section aligns with their vision.

1. Adopt a national or North American building LCA standard with prescriptive guidance for practitioners.

As described in Section 2.4, standards for WBLCA like ISO 21931-1 do exist, but the current versions of standards are not prescriptive enough on scope, LCA methods, and data sources to enable consistent results and be useful for practitioners. Canada's *National Guidelines for Whole-Building Life Cycle Assessment* are closest to providing what is needed, but they are not widely adopted and still lack some of the guidance needed by architects, engineers, or others conducting WBLCAs.

Due to this lack of a widely adopted standard, modeling methods and assumptions, life-cycle scope, and data selection vary across tools, rating systems, policies, design firms, and individuals. For example, building LCA modeling scopes vary widely. This can be due to different requirements being followed by designers (such as a green building rating system), the data available in the selected LCA tool, or simply the preferences of the LCA modeler. Commonly excluded physical scope elements include interior finishes, building services (MEP), furnishings and fixtures, and exterior site work elements. Whether some of these physical scope categories are included or excluded, as well as the extent and resolution to which they are modeled, can have significant ramifications on the comparability and reliability of WBLCA results.

There is also a need for a consistent approach to collect foreground data that is user-friendly and accurate, particularly for material inventorying (BOM) and construction data. WBLCA tools utilize different approaches to establish the material quantities that go into the LCA model, each with trade-offs related to accuracy, consistency, and user-friendliness.

Construction data is still rarely collected, despite having a large potential impact (Pearson and Waters, 2023). This may result in undercounting the importance of reducing on-site construction emissions as well as their health co-benefits for construction workers and nearby residents. Additionally, the current simplistic approach to measuring construction and installation impacts limits building LCA's ability to measure reductions from advanced building construction techniques (e.g., prefabrication) and design for manufacturing and assembly.

There are no guidelines to characterize the uncertainty of WBLCA results based on the quality and specificity of available background and foreground data or inconsistencies or errors in material quantity data. Common WBLCA tools do not yet report this variability or uncertainty in results.

Current LCA practices also do not yet account for the impact of the time of emissions on environmental impact for LCAs that study long-life products such as buildings. Development of methods to account for the time value of carbon should be considered within the developing standards.

A U.S. or North American building LCA standard that builds upon ISO standards to provide prescriptive guidance to practitioners would establish a consistent framework for practitioners to complete WBLCAs and address the challenges described above (Le Den et al., 2022; Esram & Hu, 2021). The *Whole Life Carbon Assessment for the Built Environment* (RICS, 2017) builds on EN15978 to provide more prescriptive guidance for practitioners in the UK, and is a good case study or template for this type of standard.

A U.S. or North American building LCA standard should provide clear, detailed guidance on:

- **physical scope,** describing which building elements, materials, and assemblies to include/exclude, and how those elements are classified (so that, e.g., one WBCLA result that includes MEP and finishes isn't compared to another WBLCA result that includes only structure and enclosure);
- **life-cycle scope** and how to report results for different life-cycle stages, including which stages may or may not be aggregated or reported separately;
- **LCA modeling methods** for biogenic carbon, carbon storage, and reused or recycled materials;
- **consistent modeling assumptions**, such as for default RSP, product service lives, and construction waste factors by product type. Standards can include default assumptions where project-specific data is unavailable;
- **LCIA method,** which is typically TRACI in North America. Part of the LCIA standardization would include how to address different sets of WBLCA results from before and after an update to TRACI's characterization factors;
- **background data requirements for products and materials,** including criteria for acceptable data sources and guidance around the use of generic vs. specific product data;
- **guidance on foreground data collection** to create the BOM for assessment and collect data on construction impacts;
- **guidelines on how to report uncertainty** based on the data collected, including how specific/accurate the data is and at what stage in design and construction the background and the foreground data were collected;
- **a reporting framework for building LCA results** that can be used to create alignment and standardization in how WBLCA results are reported for policies, green building certifications, or other uses. Many reporting frameworks already exist, but they vary widely since they are not tied to a standard detailing minimum requirements. Building Transparency is actively developing an "Open Carbon Building Data Format" similar to the openEPD digital format that builds off of nearly 20 existing building and infrastructure reporting schemes and will provide a helpful reference or starting point for a standardized reporting framework.

2. Fill gaps in data availability for materials and construction processes.

Building LCA requires foreground data collection (such as BOM and construction data) and background data that accurately reflects which materials and assemblies are used in the building to be helpful for measuring and reducing the embodied carbon footprint of a building.

Currently, there are primary data gaps for stages of design and construction that have historically not been the focus of embodied carbon assessments of buildings. Contractors do not yet regularly collect primary data on fuel use, construction waste factors, etc. (for the A5 "construction/installation" stage), or provide travel distances and transport types to the practitioner leading the building LCA (for the A4 "transportation to site" stage). Additionally, due to the lack of consistent standards or guidelines (described in the previous solution), the inventory of materials used on projects is collected inconsistently between projects, whether this is done by asking a contractor for a BOM or by leveraging BIM to streamline inventorying the list of materials used in the project.

In terms of background data, product-specific EPDs are not yet consistent data sources for WBLCA due to the lack of harmonization between PCRs described in Section 3.2, gaps in EPD availability for some products, and because some tools do not allow them as data options. As described in Section 2.4.2 above, generic or average LCI data is also a more appropriate data source earlier on in design when specific products have not been chosen, or if an LCA is being used to establish a baseline.

In these cases, more regionally or technologically specific LCI data is needed to improve the accuracy of WBLCA results. In some cases, this is already available, such as the region- and mix-specific data provided by NRMCA and Canadian regional ready-mixed concrete associations (e.g., southeast regional average for 4000 psi ready-mixed concrete, or USA average 5000 psi ready-mixed concrete with 25% fly ash). This type of data provides more accuracy than a single North American generic industry-wide value but is relatively rare. For example, there is no publicly available industry-average data for imported steel products from different regions, for wood products from different North American states or regions, or for aluminum products from a certain electricity mix profile. These are all examples of where having more generic data that is more regionally and/or technologically specific could improve the accuracy of WBLCA results.

Last, LCI data is completely missing for some building materials and assemblies, such as MEP products and assemblies and novel and carbon-storing materials. This can result in exclusion of critical scope, such as with MEP, as well as limiting the ability of WBLCAs to measure the decarbonization potentials of different design strategies, assemblies, and materials. For some materials, addressing the gaps in methodologies (as discussed in the Foundational LCA sections above) relating to controversial topics like biogenic carbon sequestration and storage, carbonation, mineralization, and calculating the impacts of LULUC is a necessary first step to filling the gaps in LCI data.

Expanding available data to address the challenges above requires:

- **increasing the prevalence of primary data collection for construction and transportation to the site.** This will require training for contractors, manufacturers, and LCA practitioners, and will need to be supported by templates and guidance as described in Solution 1 above. In the meantime, additional research and data collection can be used to improve the generic or average data used for these stages;
- **filling generic (non-product-specific) LCI data gaps relating to materials,** product types, and assemblies that currently have minimal data, such as MEP equipment, bio-based materials, salvaged/reused materials, and composite products such as structural insulated panels. See Foundational LCA Solution 4 above for further discussion;
- **providing geography- and/or technology-specific generic LCI data points** for materials, product types, and assemblies that already have North American industry-average LCI data. An example would be providing generic or average data to represent mass timber products produced from forests in different regions. See Foundational LCA Solution 4 above for further discussion;
- **improving EPDs as a quality data source for WBLCA**, as described in Product LCA Solution 3 above;
- **improving service life and EOL scenarios** used for use and EOL stages through additional data collection and analysis. See Foundational LCA Solution 4 above for further discussion.

3. Increase access to consistent and comparable building LCA tools.

Tools are critical for allowing architects, engineers, and other end-users to focus on foreground data collection (e.g., BOM for their building project), while the tool does the work of assigning appropriate data, applying standardized methods, and outputting results in a standardized format.

Existing building LCA tools will need to be **updated to align with the WBLCA methods and reporting standard** (described in Solution 1) and to **expand or update the scope of available background data** in the tool to meet the data quality requirements established by the standard and fill gaps in data available to practitioners (as described in Solution 2 and the Foundational LCA section). Tools like One Click LCA have historically been quick to update to align with standard updates and create versions of their tool specifically to comply with individual policies or rating systems. Longer timelines may be required for some tools before they will be policy-compliant for policies adopting newer standards or requirements. The challenge and solutions for increasing LCI/LCA dataset interoperability described in the Foundational LCA section, in Section 3.1, will support the ability of tools to do this more easily and more effectively.

Freely available building LCA tools are important for providing financially accessible options for policy compliance. University programs also often rely on free tools or tools with free educational licenses for training students. The Athena Impact Estimator is already a freely available tool that was developed in Canada and applies equally (and is widely used) in the United States.

4. Increase building LCA use, accessibility, and trust.

Widespread use of building LCA is needed to have adequate data to set policy targets or limits and so that practitioners are knowledgeable about how to comply with policies requiring WBLCA.

While there has been significant growth in the number of practitioners using WBLCA in the past few years, building LCA is still typically voluntary and often motivated by green building certifications, with a small number of firms requiring it across projects. Building LCA is sometimes perceived as too complicated for widespread use or as a tool only for firms with more time and resource availability. Adding WBLCA to the scope of services on design projects may be difficult for firms without policy requirements or client requests. There are also still not enough practitioners who know how to conduct building LCAs, and quality LCA results require both LCA skills as well as skills or mentorship from practitioners with experience in building design and construction to accurately collect inventory data.

Currently, there is no official WBLCA third-party-verification system. While there is a straightforward process and requirement for third-party verification of Type III EPDs, verification of a WBCLA is completely voluntarily and does not always make sense given the use case. Some LCA practitioners may have their WBLCAs peer-reviewed, but this is not common practice and does not provide the same quality assurance (QA) as an independent third-party-verification system. Paired with clear standards that define modeling and reporting methods, a verification or quality check system aimed at streamlining policy compliance could help ensure more consistently derived results and boost confidence in the use of WBLCA results for policy.

To reach a point of widespread understanding and use of building LCA tools and results will require expanded education and trust in building LCA tools and results through:

- **requiring or incentivizing building LCA disclosure in policy** through government procurement policies, zoning, or building codes. A recent Europe-wide study found that except for the countries where LCA is required in policies and collected in a central repository [not the case in North America], there was not sufficient data for benchmarking that was representative enough for use in benchmarks (Le Den et al., 2022);
- **providing building LCA training for practitioners** (e.g., architects, engineers) in university programs, continuing education programs for licensed professionals, and as certificates or professional training opportunities. Training should leverage tools that align with consistent standards and data sources as described in Solution 3 and ensure practitioners understand how to interpret results (find errors, understand uncertainty, etc.);
- **providing general education for policy advocates and policymakers** to understand the differences and unique role that building LCA plays as compared to EPDs, and for all building industry professionals (architects, engineers, contractors, manufacturers) to understand embodied carbon and their specific role in data collection or use of LCA results;
- **building confidence in results through practitioner credentials or verification processes for WBLCA used by policies.** In the short term, competency standards and QA processes for assessments will be aided by the clearer standards and aligned tools and datasets described in Solutions 1 and 2. In the long run, building LCAs may benefit from a verification process analogous to the third-party verification that EPDs undergo to ensure conformance with a national or North American standard as described in Solution 1. Requiring a practitioner credential or certification may be an easier route for increasing QA.

5. Collect building LCA results and material quantities in a central database.

To establish baselines for describing where we are now, researchers and/or policymakers need a representative sample of completed and openly accessible WBLCAs to create statistically derived benchmarks. While the practice of conducting WBLCAs is growing rapidly, the majority of building LCA results are not shared outside of the AEC companies that conduct them. There is no central repository for results to support the creation of transparent benchmarks. In some cases, data protection/intellectual property concerns also hinder the publication of results.

Establishing a centralized database for consistently reporting building LCA results and material quantities would enable research and the calculation of benchmarks for buildings.

This database should align with a common reporting framework outlined by a national or North American building LCA standard (as described in Solution 1). Notably, the metadata for this database would be quite significant to begin with, including a long list of project and assessment data (What type of building? What tool (and version) was used? What is the functional equivalent description? Technical performance requirements? Geography? Model scope? System boundary? etc.). Over time, the required reporting fields could decrease once analysis of available results has identified which fields are meaningful for preventing inappropriate comparisons of results.

Building LCA results and material quantities may be collected in two separate databases or the same database, as long as the same metadata on the project and the assessor is collected to help filter and establish meaningful benchmark subcategories. Collecting material quantities, based on a standardized material categorization scheme, allows for generating statistically valid benchmarks without concerns about the consistency of modeling and data choices. For example, while a building LCA results database would have to take data and tool versions and inconsistencies into consideration before comparing projects, researchers using material quantities for a set of buildings from a database could rerun building LCAs with a single tool or standard as methods and data improve to ensure consistent assumptions. A material quantity database would also allow for setting material use intensity benchmarks (Bowick et al, 2021) as a complement to carbon intensity benchmarks.

If a central database is established by a government agency or a trusted third-party organization, the database could simplify policy compliance by serving as a **central place to submit results for compliance with policies and rating systems** (e.g., LEED, Zero Carbon Certification) and could connect to existing reporting databases for voluntary commitments (SE2050, AIA DDX, etc.) and to WBLCA software tools to facilitate streamlined and accurate reporting. Automated data submission using BIM and/or building LCA tools would streamline and simplify what might seem like a complex data submission effort.

6. Set effective and appropriate baselines and targets for policy.

Benchmarks for establishing embodied carbon (GWP) performance standards and targets for buildings are a critical component of policies and rating systems, and designers also need benchmarks to inform decision-making during design. As described above, more widespread use of building LCA and a centralized repository for building LCA results would be important steps in establishing robust benchmarks.

There is still a lack of research and consensus on what subcategories or classifications for buildings are meaningful for embodied carbon benchmarking. Rigorous analysis of a significant sample size of WBLCA results would help establish *what types* of building benchmarking are useful. For instance, what level of building categorization is appropriate and meaningful (e.g., by building type, by number of stories, by climate zone, by seismic design category)? Current attempts typically focus only on building use type (e.g., school, office) to align with operational energy classifications for buildings, but operational energy classification might not be an appropriate precedent as the primary drivers of embodied carbon variation may differ from those for operational energy.

Research and user input are also needed to establish how many types of benchmarks may be needed to inform effective decision-making for different actors. A design company focusing solely on interior remodels has little need for benchmarks that include structure and enclosures. A structural engineer might benefit more from benchmarks of total material quantities. A policymaker might want different benchmarks for different points in the design and construction process. Multiple metrics, benchmarks, and targets may be needed to reflect the different needs of these actors. After establishing the type and number of benchmarks required, the repository of LCA results can be used to set baselines representing the status quo for each classification.

There is still a need for more research and lessons learned from early policy implementation around some key policy questions for driving whole-building or project embodied carbon, such as:

- *Is GWP/m^2 alone adequate for reporting and performance standards?* Setting carbon intensity per floor area (GWP/m2) alone does not incentivize designing spatially efficient buildings that can serve the same function for occupants and reduce total GWP. Reporting requirements and benchmarks for embodied carbon per capita (GWP/occupant) may address that challenge (Le Den et al., 2022), but could be misleading depending on the type of building (like a stadium that is efficient per occupant but used rarely). Alternatively, setting absolute carbon budgets based on sectoral emissions, regardless of population increase, or targeting building size through other regulations may potentially address this challenge more directly.

- *At what point in the design and construction process should regulations and incentives require reporting to be most effective?* Building LCA is used iteratively throughout the design process. The opportunity for reductions is largest at the beginning of the design process when the building design, systems selection, and reuse opportunities are still relatively flexible, but detailed models for reporting results are not available at this stage. If an LCA is submitted during permitting, how do changes in construction get accounted for? If an LCA is submitted with construction documents, how does policy motivate design teams early enough to coordinate and successfully use embodied carbon reduction strategies on their project?
- *Should policies target embodied and operational carbon together or separately? Should they incorporate other environmental impacts?* As described in Section 2.4.1, existing and developing standards for whole-life or "total" carbon accounting allow addressing operational and embodied carbon holistically to achieve the goal of absolute emissions reductions for the building sector. On the other hand, as described in Section 3.1, there are additional environmental impacts on land, water, and air that are measured by LCA that may get left out if only carbon is focused on by policy. Does addressing these impacts together or separately prevent trade-offs?
- *Which life-cycle stages should be regulated?* Current building LCA standards require cradle-to-grave analysis of the environmental impacts of a building, but existing policies often regulate only a portion of the reported life-cycle stages. For example, policies may require cradle-to-grave reporting of building LCA results but choose to only regulate upfront carbon, as is done by the City of Vancouver's Building By-law. A national or North American building LCA standard that covers the elements described in Solution 1 would ideally address this concern by providing more detailed guidance on modeling use and EOL stages.

Setting effective and appropriate benchmarks for policy will therefore require researchers and policymakers to establish:

- **a building benchmarking classification system,** including what types of building benchmark subcategories are useful and how many types of benchmarks are needed to address different scopes and checkpoints in the design and construction process;
- **a common policy framework for building embodied carbon performance** based on research and early implementation lessons learned, including reporting metrics, design and construction milestones for reporting, life-cycle scope, and whether embodied carbon should be addressed separately or in tandem with operational carbon;
- **national and/or regional baselines per classification/ subcategory**. These values should represent status quo building practice (e.g., industry average, expressed in GWP/m^2), using data collected from building LCA results that were calculated according to a common building LCA standard and reporting framework. Baseline values should be updated regularly based on data from new buildings. This "bottom-up" approach (performance thresholds calculated based on standard current practice) should provide a cost-efficient pathway for regulations to achieve carbon reductions (Le Den et al., 2022).
- **Paris-aligned building carbon budgets for embodied carbon to inform targets, incentive programs, and rating systems.** Targets complement regulatory limits by highlighting the gap between current business as usual and where buildings ought to be in order to fulfill building sector responsibilities to reduce global emissions. These targets could be used for investors/ lenders, developers, architects/engineers, and contractors to start setting voluntary project targets based on these building budgets (UKGBC Roadmap) as well as informing performance-based government incentive programs and rating systems. A target aligned with global emission goals would need to be based on the global carbon budget downscaled to budgets per building (Habert et al., 2020). Downscaling involves converting from global to national carbon budgets (per the Paris Agreement), and allocating that budget to the building sector, and then to particular buildings by type and floor area. Such budgets represent a decarbonization target, and should be updated regularly based on revisions of global carbon budget and sectoral overshoot (Le Den et al., 2022).

Table 7. Summary table of seven steps for advancing the building LCA ecosystem for policy.

Solution	Specific recommendations
1. Adopt a national or North American building LCA standard.	• Create or adopt a national or North American building LCA standard with prescriptive practitioner guidance for calculations and reporting covering scope, modeling methods and assumptions, data requirements, uncertainty, and reporting framework.
2. Fill gaps in data availability for materials and construction processes.	• Increase, through guidance and training, the prevalence of primary data collection for construction and transportation of materials to site. • Fill generic LCI data gaps relating to product types and assemblies with minimal data. • Provide geography- and/or technology-specific generic LCI data. • Improve EPDs' viability as product-specific data sources. • Expand service life and EOL scenarios data.
3. Increase access to consistent and comparable building LCA tools.	• Update existing building LCA tools to align with the national or North American building LCA standard described above, and leverage consistent background data sources where available. • Support freely available WBLCA tools.
4. Increase building LCA use, accessibility, and trust.	• Require or incentivize building LCA disclosure in policies, codes, and private sector requirements. • Provide building LCA training for practitioners (e.g., architect, engineers) through universities, continuing education, and certificate programs. • Provide general education for policy advocates, policymakers, and all building industry professionals on using and understanding building LCA results. • Build confidence in building LCA results through practitioner credentials and/or quality check or verification processes when WBLCA is used by policy.
5. Collect building LCA results and material quantities in a central database.	• Establish a central database for reporting building LCA results and material quantities that aligns with the national or North American building LCA standard described above. • Connect existing reporting databases and WBLCA tools directly to the repository.
6. Set effective and appropriate baselines and targets for policy.	• Establish a building benchmarking classification system describing the type and number of benchmarks required (e.g., type, height, level of design). • Develop a common policy framework for building EC performance • Calculate national and/or regional baselines per classification (e.g., average GWP/m^2). Use baselines to set regulatory GWP limits for new construction, updating regularly. • Establish Paris-aligned downscaled building carbon budgets to inform targets, incentive programs, and rating systems.
7. Identify prescriptive strategies and pathways.	• Provide evidence-based prescriptive strategies based on rigorous analysis of consistent building LCA results as a complementary path to GWP limits and targets for use by policies and green building certifications. • Continue to iterate over time as strategies shift.

7. Identify prescriptive strategies and pathways for reaching targets.

Many professionals desire to use prescriptive best practices learned through others' building LCAs, rather than doing an LCA themselves. However, while there are many widely accepted best practices for reducing embodied carbon through design and material selection, a list of evidence-based prescriptive strategies with a statistically derived tie to a percentage reduction at the building level does not exist at the building scale. Once building LCA has been more broadly adopted and more LCA results are available, analysis of the pool of WBLCA results should be able to reveal more quantifiably verified best practice strategies for embodied carbon reduction at the building level.

A list of prescriptive embodied carbon reduction strategies could be used to earn "points" for green building certifications and adopted as a complementary compliance path in codes and policies to simplify verification and compliance, particularly for smaller jurisdictions or projects. For example, a policy could enable projects to choose between meeting a target that represents 20% better than status quo OR documenting that their building meets a set list of strategies *(Maximum Portland cement limits? No underground structures? Use of bio-based insulation?). While high-level strategies are clear, like material efficiency in designing structural systems and using lower-carbon building materials and energy systems, additional research is required to set expected reduction values (i.e., expected % reductions that can be compared reasonably to modeled % reductions) for these strategies by building classification or subcategory.*

Note that solutions here are connected and iterative – particularly the relationship between performance-focused WBLCA and prescriptive-focused strategies. Policy requirements for WBLCA lead to increased data availability of WBLCA results. Greater data availability yields more information through which to identify those robust and evidence-based prescriptive strategies. (That is, the step of more complicated WBLCA work is necessary to get to the simpler work of prescriptive strategies.). **As prescriptive strategies become the more standard pathway to EC reductions for conventional buildings, WBLCA will always have a role in assessing novel materials and design solutions.**

3.4 Advancing Infrastructure LCA for Policy

Embodied carbon policies that leverage infrastructure LCA results will need strong standards and data that lay the groundwork for reliable and comparable project LCA results, and a framework to measure and push progress to be effective.

Infrastructure is a broad category of projects with many unique, large projects. Beginning with pavement LCA and then expanding to other roadway components and project types will make progress most feasible. Pavement LCA is a relatively straightforward subset of infrastructure, and there has already been significant research work done to support this.

The majority of roadways in the United States and Canada are completed by federal or state/provincial transportation agencies. Adoption of these solutions is therefore more contingent on interest from policymakers to invest in assessing the embodied carbon impacts of roadways. In the United States, the FHWA's Sustainable Pavements Group is well positioned to continue driving adoption of new standards, datasets, or tools, and providing training and education to transportation agencies, and will be a key player in enacting the solutions suggested in this report.

Similar to buildings, the operational carbon emissions from transportation infrastructure-related policies are significant on a global scale. Political capital and resources are limited, and for transportation infrastructure the current focus is on electric vehicles and other decarbonization strategies for operation of cars on the road, rather than construction and maintenance of the physical infrastructure. However, transportation agencies themselves likely have more control and responsibility for Scope 3 emissions from construction and maintenance than for operation of cars on the roadways they construct (Ashtiani et al., 2023).

1. Increase the number of infrastructure LCAs completed.

There are still relatively few infrastructure LCAs completed, even for pavement, due to insufficient funding, insufficient motivation, and limited staff capacity. Project-level assessments for roadways would typically need to come from transportation or other public agencies, meaning that voluntary or self-funded assessments are not possible with government-funded project structures.

Many building LCAs are currently motivated by green building certifications, but green certifications like Envision are less common for infrastructure. Additionally, adding scope (roadway LCA) may not be possible for transportation agencies without legislative direction or earmarked funding. This would also require consultants or new staff with the capacity to perform these LCAs.

To reach a point of widespread understanding and use of roadway LCA tools and results will require expanded education and implementation of policy requirements in the government agencies that typically fund and manage roadways. Solutions include:

- **setting policy that requires disclosure of LCA results for certain roadway projects.** This would increase the pool of project results, eventually informing accurate baselines by geography and project type. Consistently structured digitized results generated by public tools (Solution 3) will allow for streamlined incorporation into a central database (Solution 5 below);
- **providing LCA training for transportation agency employees** to support management and/or use of roadway LCA tools on their projects;
- **providing general education for policy advocates and policymakers** to understand the differences and the unique role that roadway LCA plays as compared to EPDs, and for all transportation industry professionals (engineers, contractors, manufacturers) to understand embodied carbon and their specific role in data collection or use of LCA results.

2. Create a North American roadway LCA standard.

Existing roadway LCA standards are not prescriptive enough to enable consistent, reliable results: ISO 21931-2 is not prescriptive enough on scope, LCA methods, and data sources, and the FHWA LCA Framework is explicitly a guidance document, not a standard.

The lack of a standard results in varying modeling methods and background data, allowing for differences across tools, policies, and individual LCA practitioners. Examples of inconsistencies are: physical scope of the assessment, life cycle stages included, construction waste assumptions, service life/replacement rate assumptions, EOL assumptions, and background datasets for products and processes. Similar to products and buildings, there are no widely adopted guidelines to characterize uncertainty of roadway LCA results based on the quality and specificity of data sources and variability or errors in modeling.

Additionally, similar to building LCA, there is a need for a consistent approach to collect foreground data for roadway LCA that is both user-friendly and accurate. Inventories (material quantities) are not consistent and reliable for pavement LCA (Bhat et al., 2021) and other infrastructure assessments.

A U.S. or North American standard for roadway LCA modeling and calculations, beginning with a standard for pavement LCA, would address these challenges. Key parameters would include:

- **a clear physical scope** as to what should be consistently included in all pavement LCAs. As standards expand to roadways, having a clear project scope for inclusion will be even more important (e.g., sidewalks and roadside vegetation? wastewater and sanitary water upgrades?);
- **a life-cycle scope** and how to report results for different life-cycle stages, including which stages may or may not be aggregated or reported separately;
- **prescriptive LCA modeling methods and assumptions** such as for allocation, reused and recycled materials, carbonation and mineralization, default service lives, and construction waste factors by product type. Standards can include default assumptions where project-specific data is unavailable;
- **an LCIA method**. This is typically TRACI in North America. Part of the LCIA standardization would include how to address different sets of roadway LCA results from before and after an update to TRACI's characterization factors;
- **guidance on foreground data collection** to create the BOM for assessment and collect data on construction impacts;
- **background data requirements for products and materials**, including criteria for acceptable data sources and guidance around the use of generic vs. specific product data;
- **guidelines on how to report uncertainty** based on the data collected, including how specific/accurate the data is and at what stage in design and construction the background and the foreground data were collected;
- **a reporting framework for LCA results,** including which reporting metrics should be used to express the embodied and/or whole-life carbon performance of the roadway.

3. Build up public background datasets and fill gaps in data availability.

As discussed throughout this report, access to transparent, publicly available background LCI data is a key step for consistent, reliable LCA results for products and projects. Similar to buildings, there are gaps in primary data collection (for construction and transportation of materials to the construction site) and in background data availability. Unlike buildings, most roadway projects are public sector projects, further emphasizing the need for this data to be public and creating a unique opportunity for roadways to lead the way for other sectors.

Addressing current background data challenges will require:

- **building up public background datasets for roadway-specific materials and processes** that align with the national standard described above and include industry-average and product-specific data points. These can then be used by EPDs as well as roadway LCA and related tools. An example of the data challenges for roadways is asphalt. Asphalt binder contributes to about 40% of the upfront carbon for an asphalt mixture GWP (A1–A5), but outdated LCI data from Europe is often used to calculate its footprint;
- **when possible, making these public LCI datasets regionally or technologically specific to improve accuracy.** See the Foundational LCA Solutions section of this report for further discussion. Concrete and asphalt in particular have short supply chains that may vary between regions, requiring more regionally specific LCI data, and more technologically specific LCI data would improve accuracy across roadway products. For example, many types and grades of asphalt binder exist, but only three types are represented in LCI data currently, with no differentiation between grades. Even with a product-specific EPD, more specific generic data that models the impact of binder grade and type would increase the accuracy of the results;
- **improving EPDs as a quality data source for roadway LCA,** as described in Section 3.2, solution 3 on PCR harmonization. EPDs will be reliable data sources for roadway LCA when relevant PCRs are harmonized across product categories, such as through the use of consistent allocation methods and background datasets for universal flows;
- **increasing the prevalence of primary data collection for construction and transportation to the site.** In the meantime, additional research and data collection can be used to improve the generic or average data used for these stages;
- **filling generic (non-product-specific) LCI data gaps** relating to materials, product types, and assemblies that currently have minimal data, such as novel or carbon-storing material technologies and roadway-specific products outside of concrete and asphalt mixes. For many prefabricated or more complex roadway components such as bioretention systems for wastewater management, light poles, traffic signals, or junction boxes, creation of this data will likely not be available for some time.

4. Increase access to roadway LCA tools.

Currently, project-scale LCA tools and assessments are primarily for pavements, excluding a wide variety of other roadway components like sidewalks, medians, bridges, and tunnels, as well as other project types (e.g., rail infrastructure, dams). Likely, pavements result in a high portion of the embodied carbon attributed to roadways, but in the long term it may be beneficial to have tools for measuring the embodied carbon of a broader range of projects and roadways components.

To expand the number and scope of infrastructure assessments possible, tools should expand to:

- **support the development of data digitization tools for transportation agencies and project teams**. Data in roadway construction is often lost (or not readily available) due to not being recorded digitally;
- **create new LCA-CAD integrated tools** to integrate with civil engineering standard design practice. Most roadway/pavement construction projects still use a form of CAD tool and use 2D models, rather than 3D tools (like most buildings);
- **update existing pavement LCA tools** to align with the standard described above and link to public background datasets where applicable. Primary data collection templates that integrate with LCA tools and connect to standardized public background datasets will facilitate a more cost-effective workflow and more consistent results across assessments;
- **evaluate which other project types (bridges, tunnels, dams, etc.) need project-specific tools** and support the creation of new public tools for infrastructure LCA beyond pavement.

5. Collect roadway LCA results and material quantities in a central database.

A central database organized around the parameters defined by the national or North American standard (Solution 1) and populated with the project LCA results prompted by the requirements in Solution 4 would allow for development and ongoing updates to project-level baselines and benchmarks for roadways to inform policy.

Compared with building LCA, a central database for roadway LCA results may be relatively simple, as a very small number of tool providers currently exist for pavement LCA in North America (e.g., FHWA, Athena), limiting potential sources for results and necessary coordination between different reporting frameworks. Additionally, data for public projects, including roadways, is typically publicly available. Transportation agencies could leverage academic researchers to support development and analysis of a results database for roadway LCAs.

6. Set regulatory limits and voluntary benchmarks.

Without benchmarks, there is little context in order to judge whether a project has reduced embodied carbon from "typical" practice or achieved a desirable target for embodied carbon per unit. However, roadway LCA benchmarks do not yet exist for North America and may be challenging to establish. Without a significant sample size and additional analysis, it is unclear what level of subcategorization of roadway types will be appropriate and meaningful when setting benchmarks. Examples of categories could include pavement maintenance, new highways, bridges, tunnels. These would likely vary regionally.

Additionally, the functional unit for roadways is not consistent or well defined. Currently, lane-mile is often used as the declared unit for roadway LCA. However, without a clear categorization of roadway types as identified above, this is somewhat meaningless. For example: one square foot of a tunnel has a significantly different embodied carbon from resurfacing one square foot of pavement.

Similar to the building LCA solutions, a policy framework that includes both limits and voluntary targets will be important. As the program evolves to include a range of infrastructure projects, it will be necessary to determine which infrastructure typologies are to be benchmarked.

The Klimatkrav program in Sweden, which benchmarks embodied carbon for a range of infrastructure construction project types and has an accompanying Klimatkalkyl tool, may be a useful model for North American infrastructure-focused policy and tools.

Showcasing low-carbon infrastructure materials and projects via a program like the Canadian Buy Clean Roadmap's "Clean Infrastructure Challenge Fund" may help to further incentivize voluntary participation and facilitate knowledge sharing.

7. Identify prescriptive strategies and pathways for reaching targets.

Use analysis of existing results data to provide evidence-based prescriptive strategies for roadway carbon reduction. This should allow for a streamlined approach to carbon reductions in most roadway scenarios while still using the performance-based approach of project LCA to assess unconventional or not-yet-assessed materials, assemblies, and project types. This would simplify education on embodied carbon reductions for roadways and result in broader adoption of decarbonization strategies.

Table 8. Summary table of seven steps for advancing the roadway LCA ecosystem for policy.

Solution	Specific recommendations
1. Increase the number of roadway LCAs completed.	• Require disclosure of LCA results for certain roadway projects in policies and rating systems. • Provide LCA training for transportation agency employees and general education for policy advocates, policymakers, and roadway professionals.
2. Create a North American roadway LCA standard.	• Create a North American roadway LCA standard with prescriptive guidance for practitioners on calculations and reporting, starting with pavement LCA. • Provide guidance and data collection templates for primary data collection and assigning secondary data that align with the national standard. • Expand to create standards for additional types of infrastructure over time.
3. Build up public background datasets and fill gaps in data availability.	• Build up public background datasets that align with the national standard, including industry-average and product-specific data. When possible, public LCI data should be regionally or technologically specific. • Improve EPDs as a quality data source for roadway LCA. • Increase the prevalence of primary data collection for construction and transportation to the site.
4. Increase access to infrastructure LCA tools.	• Support the development of data digitization tools for transportation agencies and project teams. • Create new LCA-CAD integrated tools for civil engineers. • Update existing pavement LCA tools to align with the North American standard and harmonized public background datasets. • Support the creation of new tools for infrastructure LCA beyond pavement (bridges, tunnels, dams, etc.).
5. Collect roadway LCA results in a central database.	• Create a central database for collecting roadway LCA results and material quantities for analysis and benchmarking. Leverage current tool providers and/or universities to support transportation agencies.
6. Set regulatory limits and voluntary benchmarks.	• Establish meaningful project type subcategories for roadways for baselines based on data analysis and engineer/industry input. • Calculate national and/or regional baselines (e.g., average or median GWP) by project type. • Set Paris-aligned downscaled building carbon budgets to inform targets, incentive programs, and rating systems. • Use baselines and carbon budgets to set regulatory GWP limits and incentives/targets for new construction, updating regularly.
7. Identify prescriptive strategies.	• Provide evidence-based prescriptive strategies based on analysis of the centrally collected LCA results for use by green infrastructure policies or rating systems.

4. STAKEHOLDER ACTIONS

The following table summarize the recommended actions to advance the LCA data ecosystem for policy and the proposed roles of the different stakeholders. Engagement from the full scope of stakeholders will require careful consideration to determine when and how funding support is needed to advance broader goals.

Key

The following stakeholders are included in the table:

- Policymakers / Government Agencies
- Standards Organizations (including Program Operators for product category rules)
- Voluntary Programs and Rating Systems
- NGOs / Academia
- LCA Practitioners
- Tool Developers
- Owners / Developers
- Designers (Buildings, Roadways)
- Contractors
- Manufacturers [and Trade Associations]

For each action, the proposed type of role is indicated with one of the following:

X	Indicates a **Lead** role
O	Indicates a **Support** role

Table 9. Summary table of recommended actions for foundational LCA and product, building, and roadway LCA organized by stakeholder.

	Stakeholder									
	Policymakers / Government Agencies	Standards Organizations	Voluntary Programs and Rating Systems	NGOs / Academia	LCA Practitioners	Tool Developers	Owners / Developers	Designers (Buildings, Roadways)	Contractors	Manufacturers [and Trade Associations]
Recommended Actions **Foundational LCA**										
Provide dedicated staffing and funding across agencies to maintain and update the Federal LCA Commons and Canadian LCI databases	X									
Create a multi-agency coordinated plan to fill gaps in the LCA Commons and provide better integration of the various datasets	X									
Update public datasets (e.g. Federal LCA Commons) to serve as consistent data sources for common processes and flows (electricity, fuels, transportation, heavy equipment operation, etc.)	X			O	O					
Expand and update public LCI databases to cover manufacturing of common construction materials	X			O	O					O
Update TRACI 2.1 to refer to more recent IPCC factors for GWP, distinguish between biogenic and fossil carbon flows. Dedicate funding for future updates as IPCC continues to update.	X			O	O					
Updates ISO standards to support harmonization with EN standards and provide more prescriptive guidance on compiling LCI data and LCA modeling protocols	O	X		O	O	O				O
Develop a consensus standard for evaluating the GWP benefits of carbon storage.	O	X	O	O	O	O				
Increase the availability of LCA training and university programs for LCA practitioners, designers (architects, engineers), and builders	O		O	X	O	O		O	O	O
Expand ACLCA Credential Program or similar to create a community of practice to increase practitioner consistency	O			X	X					
Expand public LCI databases to fill gaps for alternative materials and technologies	X			O	O					O
Create user-friendly tools for confidential LCA data disclosure for industry, potentially building off of the USLCI platform for accepting industry data	X					X				O
Use aggregated confidential data reported by industry to create technology- and region-specific background as part of public LCI data repositories	X									O
Improve accuracy of service life data for materials and products	X			X			O		O	O
Expand the EPA's construction and demolition debris (CDD) management data repository to include regional typical end-of-life fate for common materials	X			X			O		O	
Leverage the UNEP GLAM initiative to adopt a harmonized central nomenclature list for elementary flows for the FEDEFL. Update public data repositories to adopt the FEDEFL.	X	O		O	O	X				
Leverage GLAM's work on LCI-LCIA interoperability, so that LCI datasets operate with TRACI and LCIA results account for all items in the inventory	X	O	O	O	O	X				

	Stakeholder									
	Policymakers / Government Agencies	Standards Organizations, including P.O.	Voluntary Programs and Rating Systems	NGOs / Academia	LCA Practitioners	Tool Developers	Owners / Developers	Designers (Buildings, Roadways)	Contractors	Manufacturers [and Trade Associations]
Leverage existing programs that convert between data formats, such as GreenDelta's openLCA conversion service used by the UNEP's GLAD initiative	O				X	X				
Lead research and consensus-building among LCA experts to identify which environmetnal impacts outside of GWP policy-ready and develop pathways to overcome existing limitations to use	X			X	O					
Recommended Actions **Product LCA & EPDs**										
Require EPDs in policies, codes, and private sector (e.g. building owner) requirements	X		X				X			
Provide financial and technical assistance to support EPD production and verification	X						O			
Provide training to build capacity in government agencies and contractors to use EPDs for decision-making, before or alongside policy requirements.	X		O	X	O	O	O	O	O	O
Provide funding support to program operators for PCR development	X									O
Increase and diversify stakeholder engagement on PCR committees	O	X	O	O	O	O	O	O	O	O
Improve individual PCRs for EPD reliability and comparability (background data prescriptions, standardized specificity requirements and definitions, etc.)	O	X		O	O					O
Strengthen the verification process, potentially through requiring an accreditation	O	X		X	O					
Harmonize across PCRs through voluntary adoption of requirements across program operators (e.g. IDDI, ACLCA's Open PCR standard)	O	X	X	X	O					O
Harmonize across PCRs through mandatory PCR harmonization requirements (federal standard, conformity assessment program or similar)	X	X	X	O	O					O
Create and fund publicly available EPD generator tools that allow for two-way integration with public datasets and are aligned with updated PCRs	X	O		O	O	X				
Funding and outreach to manufacturers to increase participation in industry-wide EPD development	O			O						X
Require standardized reporting of IW-EPD representativeness and statistical measures	O	X		O	O					O
Use industry input to determine the appropriate resolution of emissions thresholds categories, in terms of product type and geographic specificity	X	O		O						O
Use EPD data and production data to establish regulatory limits and voluntary targets for each product/regional subcategory	X		X	O			X			

Recommended Actions Project LCA: Buildings	Stakeholder: Policymakers / Government Agencies	Standards Organizations	Voluntary Programs and Rating Systems	NGOs / Academia	LCA Practitioners	Tool Developers	Owners / Developers	Designers (Buildings, Roadways)	Contractors	Manufacturers [and Trade Associations]
Adopt a national building LCA standard with prescriptive practitioner guidance for calculations and reporting	O	X		O	O		O	O	O	
Increase the prevalence of primary data collection for construction and transportation of materials to site through guidance and training			O	O		O			X	
Fill generic LCI data gaps for product types and assemblies with minimal data	X			X		O				O
Provide geography- and/or technology-specific generic LCI data	X			X	O					O
Expand service life and end-of-life scenarios data	X			X	O	O	O	O	O	O
Update tools to align with national building LCA standard, including data source requirements	O	O				X				
Develop and/or support freely available WBLCA tool(s)	X					X				
Require or incentivize building LCA disclosure in policies, codes, and private sector requirements	X		X				X			
Provide building LCA training for practitioners through universities, continuing education programs for licensed professionals, and certificate programs.	O		O	X	O	O	O	O	O	O
Provide general education for policy advocates, policymakers and all building industry professionals.	X		O	X	O	O	O	O	O	O
Build confidence in building LCA results through quality check or verification processeses for WBLCA	X	X	O	O	O					
Establish a central database for reporting building LCA results and material quantities that aligns with the national or North American building LCA standard	X			X	O	O	O	O	O	
Connect existing reporting databases and WBLCA tools directly to the repository	O		X	X		X				
Establish a building benchmarking classification system describing the type and number of benchmarks required (e.g. building type, height, LOD)	X			X				O	O	
Develop a common policy framework for building EC performance, including reporting metrics and appropriate milestones for reporting.	X		O	X			O	O	O	
Calculate national and/or regional baselines per classification/subcategory (e.g. average GWP/m2)	X		O	X						
Establish Paris-aligned downscaled building carbon budgets to inform targets, incentives, and rating systems	X		O	X						
Use baselines and building carbon budgets to set regulatory GWP limits and incentives/targets for new construction, updating regularly.	X		X				X			
Provide evidence-based prescriptive strategies based on rigorous analysis of consistent building LCA results as a complementary path to GWP limits and targets for use by policies and green building certifications	X		O	X				O	O	O

	Stakeholder									
	Policymakers / Government Agencies	**Standards Organizations**	**Voluntary Programs and Rating Systems**	**NGOs / Academia**	**LCA Practitioners**	**Tool Developers**	**Owners / Developers**	**Designers (Buildings, Roadways)**	**Contractors**	**Manufacturers [and Trade Associations]**
Recommended Actions **Project LCA: Roadways**										
Require disclosure of LCA results for certain roadway projects in policies, private sector projects, and rating systems	X		X				X			
Provide LCA training for transportation agency employees and general education for policy advocates, policymakers, and roadway professionals	X		O	X	O	O	O	O	O	O
Adopt a national roadway LCA standard with prescriptive guidance for practitioners on calculations and reporting, starting with pavement LCA.	O	X		O	O		O	O	O	
Provide guidance and data collection templates for primary data collection and assigning secondary data that align with the national standard	O	X		X	O			O	O	
Build up public background datasets that align with the national standard, including industry-average and product-specific data	X			X	O					O
Increase prevalence of primary data collection for construction and transportation to the site	X					O			X	
Create data digitization tools for transportation agencies and project teams.	O					X		O	O	
Create new LCA-CAD integrated tools for civil engineers	O					X		O		
Update existing pavement LCA tools to align with the North American standard and harmonized public background datasets	O					X				
Create new tools for infrastructure LCA beyond pavement (bridges, tunnels, dams, etc.).	O					X				
Create a central database for collecting roadway LCA results and material quantities for analysis and benchmarking. Leverage current tool providers and/or universities to support transportation agencies.	X			X		O	O	O	O	
Establish meaningful project type subcategories for roadways for baselines based on data analysis and engineer/industry input	X	O	O	O			X	O	O	
Calculate national and/or regional baselines (e.g., average or median GWP) by project type	O		O	X						
Set Paris-aligned downscaled carbon budgets to inform targets, incentive programs, and rating systems	O		O	X						
Use baselines and carbon budgets to set regulatory GWP limits and incentives/targets for new construction, updating regularly.	X		X				X			
Provide evidence-based prescriptive strategies based on analysis of the centrally-collected LCA results for use by green infrastructure policies or rating systems.	X		O	X				O	O	O

5. CONCLUSION

In the recent past, as manufacturers produced more EPDs and more organizations started doing project LCAs, policymakers weighed the timeliness and readiness to develop and implement LCA-based policies and decided to begin leveraging LCA for industrial and building–focused climate policy. Looking ahead, now that many LCA-based policies have been developed and are being implemented, there is a growing need to make the system of EPDs and project LCAs more robust.

The effectiveness of these policies will depend on the underlying LCA ecosystem. This ecosystem, comprising standards and guidelines, data sources, tools, and people, will need to support LCA results (EPDs, building and roadway LCAs) that are available, accessible, consistent, and reliable. And it must support people that can make good use of these results to implement effective policy.

An idealized LCA ecosystem that supports effective policy would be: **transparent**, **accessible**, **up to date** with new materials, technologies, and processes, **effective in providing comparable and reliable results**, and **harmonized** across countries and regions, and across scales (e.g., products and projects).

This report provides a roadmap for strengthening the LCA ecosystem, focusing on four interrelated networks within that broader system: foundational LCA (which provides the foundation for the other three), product LCA, building LCA, and roadway LCA. While the recommended solutions address challenges specific to each of these four subsystems, they all follow a general progression:

- **Improve standards** to be more detailed and prescriptive for consistency and quality.
- Increase the availability, accessibility, and quality of **public background data**.
- Provide **access to tools** that streamline processes (to facilitate the production of more product and project LCAs) and align with standards (for more consistency and quality across assessments).
- Provide **support (e.g., financial, technical, education)** so that more people and organizations can conduct LCAs.
- Create **meaningful benchmarks** for policies, drawing upon the improved sets of LCA results (due to the combined effect of the stronger standards, data, tools, and actor representation from the previous steps).

While the list of solutions is long, there are relatively few cases where brand-new structures or programs are required. New initiatives that aim to recreate and replace existing pieces can slow progress unnecessarily. To better support decarbonization, the emphasis should be on strengthening the existing system and the current efforts already underway. By supporting, aligning, and building upon current efforts, and filling gaps where necessary, the collective action of stakeholders can make real the vision of a healthy LCA ecosystem to support effective policy and reduce carbon emissions.

DEFINITIONS

Accuracy [of LCA results]: the degree that the LCA result reasonably reflects reality; "the degree to which the result… conforms to the correct value" (Oxford Languages https://languages.oup.com/google-dictionary-en)

Allocation: "partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems" (ISO 14040).

Allocation often relates to the scenario where a facility produces multiple products and/or by-products, and the collected data (e.g., for energy use) is for the aggregated production process, (i.e., does not distinguish between separate processes specific to each product). Thus, in order to avoid double-counting and/or undercounting, the LCA must allocate a portion of total facility processes (e.g. energy use) and corresponding environmental impacts to each product system.

> Example: a blast furnace that creates both iron and slag. Allocation may be used to assign some portion of the total environmental impacts of the blast furnace to each of these output materials.

Allocation principles and procedures also apply to reuse and recycling situations, including closed-loop systems ("material from a product system is recycled in the same product system") and open-loop systems ("material from one product system is recycled in a different product system") (ISO 14044: 2006).

Allocation method: a method used to partition flows between product systems.

Common methods for allocation when assessing multiple co-products produced through a single process include: allocating by physical properties (e.g. mass); and allocation by economic value. (Note: ISO 14044 states: "Whenever possible, allocation should be avoided" by dividing the unit processes into multiple subprocesses, or expanding the product system so as to include all co-products and by-products.)

Common methods for allocation when assessing product systems with recycled input and output materials include: the recycled content ("cut-off") approach (which credits recycled input materials by treating them as burden-free); and the avoided burden (aka EOL) approach (which credits recycled output materials for avoiding virgin material production in a downstream system). There are also hybrids of these two approaches.[16]

16. See Bergsma & Sevenster (2013); Annex A provides a useful description of these approaches.

Average data: "data derived from specific production processes" which has been aggregated (EN 15804:2012+A2:2019).

> Example #1: specific data collected from each of a supplier's multiple facilities that is later aggregated to provide a facility-average dataset for that manufacturer.
>
> Example #2: specific data collected from multiple manufacturers which is combined to create an industry-average dataset (for, e.g., an industry-average EPD).
>
> Example #3: data collected from one manufacturer's facility that represents an average across a group of similar products.

Background data, aka **secondary data:** the indirectly measured, calculated, or obtained quantified value of a unit process or activity and related information within a product system's organization, not based on specific original source measurements (Source: ISO 21930:2017, 3.5.2).

Building model: refers to the physical characteristics of a building for the purpose of their quantification and categorization. It may be used for different levels of aggregation, from the product level to the building element level (adapted from EN 15978, where no definition is provided).

Bill of materials (BOM): an extensive list of the types and quantities of materials and products included in a project to be accounted for in the project LCA. A project LCA maps each item in the BOM (e.g., fabricated structural steel plate – 6.25 metric tonnes) to background LCI or LCIA data in order to generate the project LCA results. The BOM often accounts for the additional material quantities consumed beyond what is initially installed (due to, e.g., construction waste and replacement).

Carbon footprint of a product (CFP): the sum of the GHG emissions and the GHG removals in a product system, expressed as CO2 equivalents (CO2e) and based on an LCA using the single impact category of GWP.
Note: A CFP can be disaggregated into specific types of emissions and removals (e.g., fossil, biogenic, and land-use GHG emissions), and/or disaggregated into separate life-cycle stages (adapted from ISO 14067:2018, see ISO, 2018).

Carbonation: the chemical reaction that occurs when carbon dioxide [CO2] in the air reacts with calcium hydroxide [Ca(OH)2] in cement to form calcium carbonate [CaCO3]. This can contribute to the drawdown of carbon dioxide from the atmosphere to be stored in the concrete. Carbon dioxide can also be injected directly into the concrete mix before it is poured.

Comparability [of LCA results]: the extent to which LCA results can be appropriately compared – a function of (i) the extent to which the objects of assessment are functionally equivalent, and (ii) the extent to which the LCAs use equivalent modeling methods and data sources (so that differences in results are due to differences in actual emissions rather than artifacts of the modeling process).

Data source: the place of origin of information about the environmental impact of an energy source or input material considered in an LCA.

Downstream (in the value chain or life cycle): processes following a life-cycle stage.

> Example: product use and EOL are downstream of a product's manufacturing stage.

Environmental product declaration (EPD): a third-party-verified document based on an LCA model, written in conformance with international standards, that reports the environmental impacts of a product. Common scopes include:

> **Cradle-to-gate EPD:** accounts for the environmental impacts of the "product stage" of the life cycle (modules A1–A3) only: resource extraction / raw material acquisition and manufacturing.
>
> **Cradle-to-grave EPD:** accounts for the environmental impacts of the whole life cycle: raw material extraction through installation, use, replacement, and EOL (stages A, B, and C).

Foreground data, aka primary data: the quantified value of a unit process or an activity obtained from a direct measurement, or a calculation based on direct measurements at its original source (SOURCE: ISO 21930:2017, 3.5.1).

Functional equivalent: "quantified functional requirements and/or technical requirements for a building or an assembled system (part of works) for use as a basis for comparison" (EN 15978, adapted from ISO 21931-1:2010).

Objects (e.g., two products or two buildings) are considered functionally equivalent if they provide similar performance in their end-use application.

Generic data: "data that is not directly collected, measured, or estimated [in either the foreground or the background system], but rather sourced from a third-party LCI database or other source" (European Commission, 2021).

> Example: an EPD uses generic LCI data for combustion of diesel fuel, collected independently of the particular EPD or any upstream suppliers.

Global warming potential (GWP): the potential climate change impact of a product or process as measured by an LCA, reported in units (typically kilograms) of carbon dioxide equivalent (CO_2e).

Guides/guidance/guidelines: non-formal documents, typically nonmandatory, that provide recommendations, general direction, and advice for the technical criteria, methods, processes, and practices of a WBLCA. Guidelines can be developed by anyone and they do not require the formal consensus of technical experts.

GWP benchmark, baseline, threshold, limit, target: each of these related terms refers to a static GWP value, used (directly or indirectly) for comparisons. The terms can differ in whether they are descriptive/informative (i.e., they describe "what is" – the current or a future state) or normative (i.e., they explicitly support a policy or other agenda – "what should be"). Their use can also vary in terms of whether they are performance-neutral or represent some particular level of performance (e.g., low, average, or high).

The terms are not always used consistently throughout the industry. This report generally uses these terms to mean the following:

- **Benchmark:** a "reference point against which comparisons can be made" (ISO 21678:2020, see ISO, 2020).
  Benchmark is the most inclusive term here: it is more general than a baseline in that it can represent low, average, or high performance; it is usually calculated based on existing product or project data, but could be determined otherwise (e.g., downscaled global carbon budgets). The generic term "reference value" is often used similarly.

- **Baseline:** a reference point to be used as a basis for comparison that generally aims to describe current business-as-usual performance; it is typically derived from representative industry data.

  > Example: the CLF Material Baselines draw upon current industry data to provide average GWP values for a range of product types. Policies and programs can use these baselines to inform limits, targets, etc.

- **Threshold [or Regulatory] Limit:** an upper acceptable GWP threshold for mandatory compliance (i.e., minimum performance); it is typically set for a particular policy or program.

  > Example: "The threshold approach defines a

maximum GHG emissions intensity for each category of material" (Dell, 2020).

Example: The Buy Clean California Act employs GWP limits for specific materials, where products must fall below the limit to comply.

*Some documents use the term "**emission standard**" or **"performance standard**" to refer to this concept. Because this report uses the term "standard" frequently to describe a different concept (a document that provides LCA rules and methods), we are avoiding the use of "emission standard" or "performance standard" here to minimize confusion.*

- **Target:** a voluntary high-performance (i.e., low-GWP) goal to aim toward. Programs/policies may include short-, medium-, and long-term target values (ISO 21678:2020).

  Example: Ramboll's EC building benchmarks report calls for "setting targets that are aligned with the 2015 Paris Agreement to support the built environment's transition to a lower-carbon future" (Le Den et al., 2022).

Interoperable; interoperability: the ability of a system to work with other systems, specifically with the aim of exchanging and making use of information. In the context of this document, the term "interoperable" sets out the ambition that measurement and accounting rules could align, or become harmonized, making the calculations and results comparable and usable between one tool/system and another.

Life-cycle assessment (LCA): a systematic set of procedures for compiling and evaluating the inputs and outputs of materials and energy, and the associated environmental impacts directly attributable to a product or process throughout its life cycle. An LCA of a building is often called a WBLCA.

Life-cycle impact assessment (LCIA): a phase of LCA used to quantify the potential environmental impacts of a product or process. "LCI results are associated to environmental impact categories and indicators. This is done through LCIA methods which firstly classify emissions into impact categories and secondly characterize them to common units so as to allow comparison" (EPLCA, n.d.).

Life-cycle inventory (LCI): a phase of LCA involving the data collection and quantification of inputs and outputs associated with a product or process throughout its life cycle. Such inputs and outputs include energy, raw materials, other physical inputs, and emissions to air, land, and water.

Life-cycle stages: discrete portions of a product's or a project's life cycle, separately accounted for in a LCA. The "product," "construction," "in-use," and "EOL" stages are subdivided into more specific **modules** such as A1, A2, etc. (though these are also sometimes referred to as "stages"). See Figure 10 (page 65).

Service life (and other LCA-related terms describing a specified amount of time):

- **Service life:** period of time after installation during which a building or its component parts meet or exceed the performance requirements (ISO 21931-1). Also referred to as "working life" in the EN 15978 definition.
- **Design life:** service life intended by the designer (ISO 21931-1).
- **Estimated service life:** service life that a building or parts of a building would be expected to have in a set of specific in-use conditions, determined from reference service life data after taking into account any differences from the reference in-use conditions (ISO 21931-1).
- **Required service life:** service life (of a building) required by the client or through regulations (ISO 21931) (EN 15643-1:2010).

Object of assessment: the building, including its foundations and external works within the perimeter of the building's site, over its life cycle. The perimeter used to characterize the site shall be consistent with the definition and intended use of the building (EN 15978).

Product category rule (PCR): a set of specific rules, requirements, and guidelines for conducting an LCA and developing Type III environmental declarations for one or more product categories. PCRs are reviewed and improved periodically over time. Each material's PCR dictates methodological decisions that are relevant and fine-tuned to the material supply chain of that product category (e.g., concrete, floor coverings, insulated metal panels, etc.). A PCR dictates which life-cycle stages and scopes must be included in the LCA, which background data sources are acceptable or mandatory, and other modeling choices such as allocation method and impact assessment method.

Product environmental footprint (PEF): an LCA-based method to quantify the environmental impacts of a product. With much overlap and some differences compared to EPD methodologies, the PEF is the European Commission's alternate schema for assessing and reporting the EF of products, currently in a transition phase before potential adoption as policy.

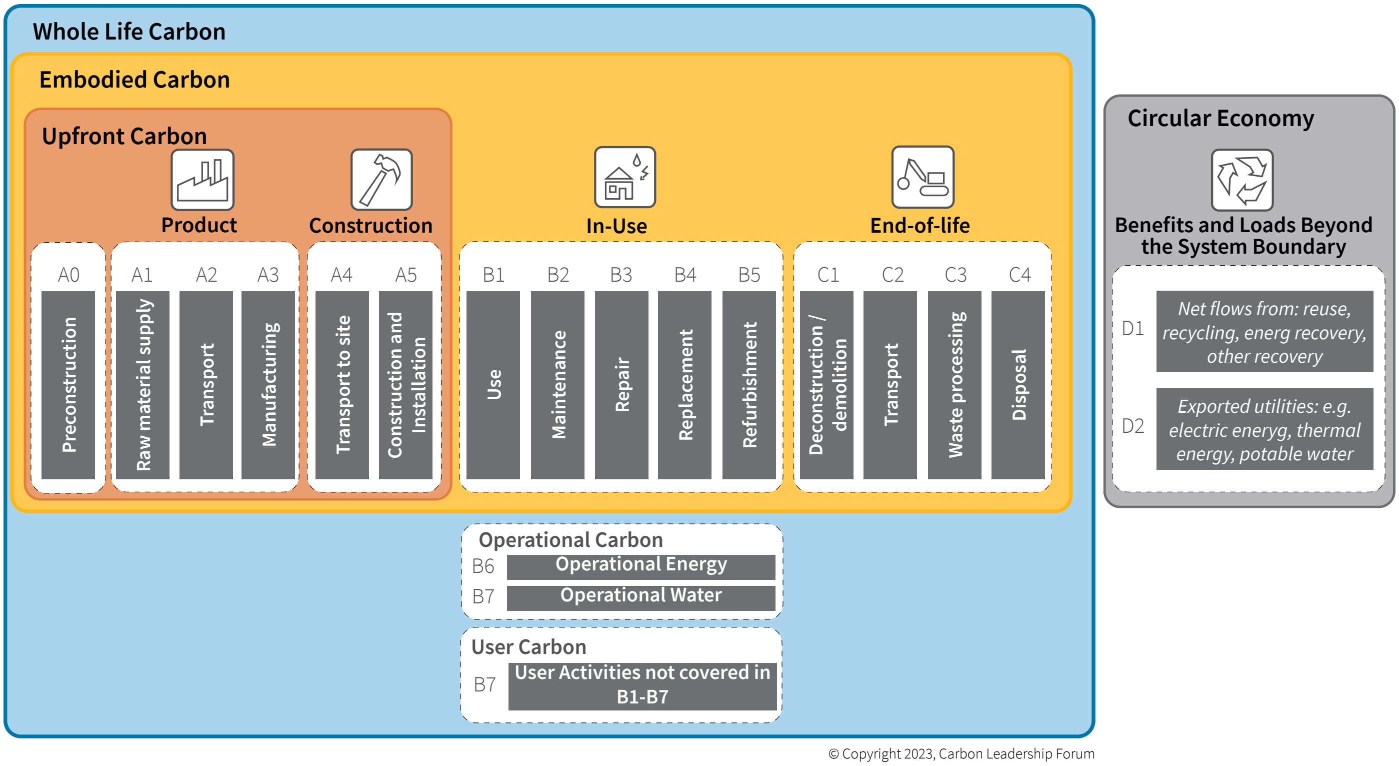

Figure 10. Life cycle stages for building products, adapted from RICS Whole Life Carbon Assessment DRAFT 2nd Edition (2023).

Proxy data: "approximate data [from, e.g., a similar product or process] if no system specific data or generic data are available" (ISO 21930:2017, 3.5.5).

Reference study period (RSP): period over which the time-dependent characteristics of the object of assessment are analyzed (ISO 21931) (EN 15978).

Reliability [of LCA results]: the degree to which the LCA result can be depended on to be accurate. (Adapted from Oxford Languages https://languages.oup.com/google-dictionary-en.)

Specific data: "data representative of a product, product group or construction service, provided by one supplier" (EN 15804:2012+A2:2019).
Sometimes this is modified to describe a particular aspect of specificity, such as "facility-specific" (data from one facility, not an average of data from across a manufacturer's multiple facilities).

Standards: formal documents, typically mandatory, that establish uniform technical criteria, methods, processes, and requirements for WBLCA. They are typically produced by third-party standardization organizations and require the formal consensus of technical experts before publication.

Upstream (in the value chain or life cycle): processes preceding a life-cycle stage.

> Example: raw material extraction is upstream of a product's manufacturing stage.

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APPENDIX A: ONGOING INITIATIVES

Highlighting existing initiatives to reduce redundancy and accelerate action is one of the three primary goals of this report. Section 2 "Exploring the Current LCA Ecosystem" highlights standards, data sources, and tools that already exist or have been published. This appendix highlights ongoing initiatives related to the solutions laid out in the roadmap in Section 3 that are still in development or may continue to evolve in the future.

Table A1 is organized according to the four sections of the roadmap – Foundational LCA, Product LCA, Building LCA, and Roadway LCA – and is loosely organized in the order of the steps in each section.

A Note on Future Expansion

Highlighting ongoing work is a challenge, as these initiatives may be discontinued or change goals. However, the CLF has identified the following as key ongoing initiatives that have the potential to address solutions highlighted in our roadmap. If this appendix is helpful to readers of this report, the CLF may continue to update and expand this list. If you are aware of initiatives that are critical and missing from this list, please consider sharing them with info@carbonleadershipforum.org with the subject line "Advancing the LCA Ecosystem: Ongoing Initiatives Recommendation."

Table A1. Summary of ongoing initiatives related to the solutions proposed in this report.

Foundational LCA	
Federal LCA Commons	A collaboration among 8 federal agencies and labs (USDA, NREL, NETL, EPA, Argonne National Lab, FHWA, DOE, and the U.S. Forest Service) to provide transparent and publicly accessible data and methods to inform life-cycle decision-making. Serves as a central access point for a collection of free public LCA data repositories.
Low Carbon Built Environment Challenge program (Construction Research Centre at the NRC)	Aims to address the need for knowledge and data to identify and develop low-carbon materials, products, services, tools, and practices in Canada's construction sector through supporting industry-developed carbon accounting tools, low- and zero-carbon construction materials, establishing a national LCI datasets repository for construction materials, and improving decision support tools for optimized low-carbon building and infrastructure design, procurement, operation, and EOL management. Builds off of the work of the Low-Carbon Assets Through Life Cycle Assessment initiative (LCA^2) that ran from 2019 to 2023.
Life Cycle Assessment Certified Professional (ACLCA)	A credential program for LCA professionals requiring an exam, a degree in LCA, and demonstration of professional experience (including a peer-reviewed LCA). Requires recertification every 3 years upon completing continuing education.
Global LCA Data Access Network (GLAD) (UNEP Life Cycle Initiative)	An open-source project that supports accessibility and interoperability of LCA data. Has a directory/search tool for accessing LCA databases from independent providers worldwide that connects to GreenDelta's openLCA conversion service. Currently, GLAD is working on a system for organizing and managing a central nomenclature list of elementary flows.
Global Guidance for Life Cycle Impact Assessment Indicators and Methods (GLAM) (UNEP Life Cycle Initiative)	A program of the Life Cycle Initiative (an international public–private partnership hosted by UNEP) working to make recommendations on LCIA indicators and characterization factors. Focused since 2020 on working toward creation of a global LCIA method, including classification, midpoint and damage characterization, normalization, and weighting to assess the life-cycle impacts of products and services on human health, ecosystem, and natural resources.

Product LCA	
EPD Technical Assistance Program (U.S. EPA)	$250 million program via s. 60112 of the Inflation Reduction Act of 2022 to provide grants, technical assistance, and tools to construction material manufacturers for developing and verifying EPDs and/or to states, tribes, and nonprofits that support construction material manufacturers. Can also spend this funding on other activities that assist in measuring, reporting, and reducing embodied carbon from products and materials.
openEPD (Building Transparency)	An international open data format for passing digital third-party-verified EPDs among program operators, EPD databases, life-cycle analysis tools, design tools, reporting, and procurement.
ILCD+EPD Data Format	A standardized digital EPD format created by the International Life Cycle Data System of the European Commission. EPDs compliant with openEPD are compliant with ILCD+EPD by default.
Addendum: Digital EPDs / openEPD (ACLCA)	Guidance in development as part of the ACLCA Open PCR Standard for an open data format for reporting and exchanging EPD information, building off of the openEPD standard developed by Building Transparency.
Addendum: Biogenic Carbon Accounting (ACLCA)	Guidance in development as part of the ACLCA Open PCR Standard for calculating the carbon flows and carbon storage in organic/biological-based products.
Addendum: Uncertainty methodology (ACLCA)	Proposed addendum to the ACLCA Open PCR Standard to develop a methodology for calculating uncertainty for EPDs, to be adopted by program operators during PCR development.
Addendum: Data Specificity in EPDs (ACLCA)	Guidance in development as part of the ACLCA Open PCR Standard that defines different types of EPDs (facility-specific, manufacturer-specific, etc.) and provides a taxonomy for EPDs related to product specificity, manufacturing specificity, and supply-chain specificity.
CLAR (ACLCA) certification	A higher-level credential building off of the LCACP program that requires an additional 5 years of experience and at least 5 critical reviews of an LCA to apply. Aims to identify LCA professionals qualified to provide peer (or third-party) review of LCA studies, PCRs, and EPDs.
IDDI – PCR harmonization for cement, concrete, and steel (UN Clean Energy Ministry)	A global coalition of governments and private sector organizations working to stimulate demand for low-carbon materials through green public procurement. Co-led by India and the UK, with Canada, Germany, Japan, Saudi Arabia, Sweden, the United Arab Emirates, and the United States as members. One of the projects is providing guidance on harmonization of cement, concrete, and steel PCRs, developed in spring 2023 and up for public review in summer 2023.
MEP 2040 Commitment	A voluntary commitment for MEP engineering and design firms. Currently, it focuses on establishing a company plan, requesting low-GWP refrigerants, requesting EPDs, and participating in regular forums. Contributes to filling gaps in data availability for MEP, in addition to providing education and training opportunities for MEP engineers.
Building LCA	
Proposed ASHRAE/ ICC Standard 240P – Evaluating Greenhouse Gas (GHG) and Carbon Emissions in Building Design, Construction and Operation	A developing standard for the assessment of carbon emissions (both operational and embodied) across the entire building life cycle. The proposed standard will cover calculation methodologies for net zero GHG emissions, GHG and carbon emissions associated with on-site and off-site material, energy and carbon flows, and embodied GHG and carbon emissions of materials and systems. It will be referenceable by policies and codes in the United States, but it is an international standard and may require a North American addendum to provide geography-specific guidance.

Adoption of ***National Guidelines for Whole-Building LCA*** as a Canadian standard (National Research Council Canada)	Published in 2022, this is the most comprehensive and detailed instruction guide available for WBLCA in Canada, and is based on EN 15978 and ISO 21930 and with a specific purpose to improve quality and consistency of WBLCA. This document may soon begin the process of becoming a Canadian standard and/or undergo edits for a second edition through the NRC's Low Carbon Built Environment Challenge program.
(DRAFT) Prestandard for Calculation Methodology for Structural Systems in Whole-Building LCA	A prestandard for establishing a calculation methodology for structural engineers to perform WBLCA on structural systems, being developed by the Structural Engineering Institute (SEI) of the American Society of Civil Engineers (ASCE). It will have multiple tiers establishing different levels of detail for reference by other standards and reporting initiatives.
Contractor's Commitment to Sustainable Building Practices (Sustainable Construction Leaders Peer Network)	A voluntary commitment for contractors started in 2018 and focused on carbon, job-site wellness, waste management, water management, and material selection. Voluntary carbon criteria include tracking of fuel and utility usage on site and for corporate operations, tracking the embodied carbon of materials for self-performed work, tracking fuel usage for deliveries and waste hauling, tracking emissions from waste processing for construction waste, and tracking refrigerant leakage for corporate controlled facilities. This initiative has the opportunity to fill gaps in data availability for A5 and support training of contractors in primary data collection for construction and installation processes used in LCA.
WBLCA benchmarking infrastructure phase 2 (Athena Sustainable Materials Institute)	Guideline for how to source and organize a BOM for WBLCA, plus data quality assessment and effect of data quality and completeness on uncertainty of results. Part of a larger project creating the pieces to enable robust benchmarks.
Athena Building LCA Web app and API	Athena software tools, which are already freely available, will be further increasing accessibility by creating a web version of the Impact Estimator. This is a highly advanced new tool scheduled for release late 2023. Athena will also develop an API in 2024, to enable links with other building industry tools for even more accessibility.
BCIT Whole-Building Life Cycle Assessment Professional Microcredential Program	The British Columbia Institute of Technology (BCIT) partnered with Athena Sustainable Materials Institute to develop the first professional credentialing program in WBLCA. This microcredential is a four-course continuing education program delivered remotely, and an excellent example of expanding opportunities for building LCA training for practitioners.
2030 Commitment and AIA 2030 Data Design Exchange (DDx) (American Institute of Architects (AIA))	A voluntary commitment for architecture firms, launched in 2010, that requires annual reporting to the AIA 2030 Design Data Exchange (DDx). Beginning in 2020, the AIA also started collecting embodied carbon data for buildings. Contributes to building LCA data collection, as well as supporting broader use of building LCA by architects.
SE 2050 (Structural Engineers 2050 Commitment Program) Commitment and Reporting Database	Developed by the Sustainability Committee of the SEI of the ASCE and designed to support structural engineers in meeting the challenge issued in 2019 by the CLF: "All structural engineers shall understand, reduce and ultimately eliminate embodied carbon in their projects by 2050." Structural engineering firms participating in SE 2050 report structural embodied carbon (GWP) data from building LCAs to a central repository, the SE 2050 Database. This data is then used to inform industry benchmarks and targets, ultimately working toward net zero embodied carbon by 2050.

Climate Positive Design Challenge	Challenges landscape architects to commit to being climate positive by 2030, and to design their projects to remove more carbon from the atmosphere than they emit, starting immediately. The Pathfinder tool is used to automatically report progress on this commitment, and contributes to data collection of sitework and education opportunities for landscape architects.
Open Carbon Results Reporting Schema (Building Transparency)	A common project information and embodied carbon reporting schema that provides a common language for collecting project information and embodied carbon data. Aims to provide a schema for consistent and comparable project-level embodied carbon metadata across certifications, commitments, and policies that will collect building and infrastructure LCA data. Members of the ECHO Project are participating in development of the schema, with the goal of consistent minimum reporting across initiatives.
CLF WBLCA Benchmark Study Version 2 (Carbon Leadership Forum)	In 2017, the CLF published the Embodied Carbon Benchmark Study for North American buildings. The new CLF WBLCA Benchmark Study (Version 2) will expand our research methodology and result in geographically and typologically specific benchmarks for buildings, systems, and assemblies modeled with consistent scope and background data. This will allow designers and decision-makers to set reliable embodied carbon targets and understand the potential for reduction throughout the design and construction processes.
Construction Sector Digitalization and Productivity Challenge program (Construction Research Centre at the NRC)	Aims to support digitization and performance-based design and building requirements in the construction sector through research to support the implementation of performance-based construction codes, developing a roadmap to help guide the digitalization of the construction sector, modular construction R&D, and R&D to support the development of digital portals for submitting electronic building plans and permits and to support virtual inspections.
Embodied Carbon Harmonization and Optimization (ECHO) Project	Beginning in March 2023, the following built environment industry leaders have been discussing a potential coalition to accelerate and strategize how to rapidly reduce embodied carbon in the built environment: Architecture2030, Building Transparency, the Carbon Leadership Forum, the International Living Future Institute, the U.S. Green Building Council, A&D Materials Pledge & 2030 Commitment (the AIA), the Contractors Commitment, the Climate Positive Design Challenge, the American Society of Landscape Architects, the MEP 2040 Commitment, the ASCE (Infrastructure 2050 and SEI SE 2050 Commitment), and the Urban Land Institute. The first two initiatives of this coalition are to participate in development of Building Transparency's Open Carbon Results Schema for buildings and to draft North American minimum embodied carbon project reporting guidelines.
Roadway LCA	
Infrastructure 2050 (ASCE)	This commitment is still in development by ASCE and has not yet been launched. When launched, it will be a voluntary commitment for infrastructure designers to target net zero by 2050 on their projects. It may involve either product- or project-level embodied carbon reporting.
Sustainable Pavements Program (FHWA)	Started 10 years ago, it has a technical working group, publishes research and educational resources on the state of knowledge related to sustainability of pavements, and led development of a pavement LCA tool based on stakeholder input that uses public data sources and EPDs. The program is a key forum for bringing together experts and public agencies from across the country to share knowledge and best practices.

APPENDIX B: PCRS RELEVANT TO CURRENT U.S. EMBODIED CARBON POLICIES

As described in Section 2.3.1, PCRs are critical standards for increasing the reliability and comparability of EPDs in policy. The following are example PCRs relevant to current policies, along with brief descriptions of selected items related to the LCA ecosystem.

- **UL PCR for Building Related Products and Services Part A**: The UL "PCR Part A" serves as an intermediary document between ISO 21930 (sometimes referred to as the "core" PCR for building products) and UL's category-specific "Part B" PCRs (for, e.g., flooring or steel construction products), which serve in tandem with Part A. Part A provides requirements and guidelines applicable to all building product types (e.g., default allocation methods), more specific to UL's program than what is in ISO 21930, but without category-specific content. UL's organization with one Part A and multiple Part B PCRs mirrors the German EPD program Institut Bauen und Umwelt e.V. (IBU). Other North American program operators with a Part A PCR include Smart EPD and Sustainable Minds.
- **UL PCR Part B for Designated Steel Construction Products** is an example of a UL Part B "subcategory" PCR. It builds on Part A with more category specificity. For example, the Data Sources section first references Part A (which has generic requirements about data sources) and then provides additional steel-specific guidance: "Data sources shall be documented per Part A, Section 3.1. All steel datasets shall be the most recent, representative, regional-average datasets published by AISI or Worldsteel, unless data is available from the specific steel supplier for the construction product covered by the EPD."
- **NSF International PCR for Concrete** serves as the primary PCR for ready-mix concrete in North America. This PCR is an example of how current PCRs are addressing data challenges related to upstream emissions: Portland cement production is the dominant contributor to a concrete product's total GWP, but is produced upstream (i.e., concrete producers do not produce cement, but use cement they purchase from a supplier). Since cement production is both a significant contributor to concrete GWP and varies from supplier to supplier, a concrete LCA's choice of secondary cement data is significant in terms of EPD result accuracy (how well it reflects reality) and comparability (the extent to which differences in results are due to actual emissions rather than to modeling/data differences).

  The concrete PCR defines the default cement data sources as: (i) product-specific EPD when it exists (preferred), and (ii) IW-EPDs: prescribed specific ones are listed by geography (United States and Canada) and cement type.

- **The National Asphalt Pavement Association's (NAPA) PCR for Asphalt Mixtures (version 2.0)** represents significant work in developing a PCR that supports the creation of consistent and reliable EPDs (NAPA, 2022). The template LCA model created as part of the PCR development, NAPA's EPD generator tool Emerald, and this PCR were developed in parallel to support the generation of comparable EPDs. The PCR explicitly prescribes background datasets for many processes, and the asphalt mixture LCA framework and accompanying datasets are available in the Federal LCA Commons.
- The **National Glass Association (NGA) PCR for Flat Glass, published by NSF International**, has an example of some of the flexibility allowed LCA modelers in current PCRs. The Flat Glass PCR requires that energy production data is "aligned with the region (region shall be used from most local and relevant sources being from local power grid, state power grid, country sub-regional power grid, to least of a national power grid) of manufacture." This open-endedness allows the LCA modeler to choose energy data sources, potentially limiting the comparability of EPD results for this category without additional reporting.

Table B1 includes a more comprehensive list of PCRs that are relevant for current policies in North America. The CLF then assessed each PCR in this list to answer the question: To what extent could an update to the PCR lead to significant embodied carbon reductions? This initial effort is simple and coarse: the CLF scored each PCR simply as either a "1" or "2" priority and then organized within these two categories by MasterFormat. This method could be refined in the future.

PCRs were sorted into priority 1 or 2 qualitatively as a function of: (i) embodied carbon significance – i.e., how impactful the products currently are or could be in terms of EC emissions; and (ii) current limitations to appropriate comparability that could be addressed in the PCR. That is, a PCR is prioritized if product choices in the category could yield significant carbon reductions AND improvements to the PCR could help facilitate those choices.

Table B1. PCRs relevant to current U.S. embodied carbon policies. "Div" refers to MasterFormat division. Within priority categories 1 and 2, PCRs are organized by MasterFormat division. Shaded expiry cell means PCR set to expire in 2023.

Div	Issuer	PCR name	Date issued	Expiration date	Version	Status	Priority
00	UL Environment	**UL PCR for Building Related Products and Services Part A**	3/28/2022	unknown	4	Active	**1**
00	Smart EPD	**Smart EPD PCR Part A**	*TBD*	*TBD*	–	In development	**1**
03	ASTM	**Slag Cement**	12/31/2020	12/31/2025	2	Active	**1**
03	ASTM	**PCR for Precast Concrete – UNCPC: 37550**	5/30/2021	4/30/2026	3.0	Active	**1**
03	NSF International	**Concrete**	2/22/2021	2/22/2024	2.2	Active	**1**
03	NSF International	**Portland, Blended, Masonry, Mortar, and Plastic (Stucco) Cements**	3/31/2020	3/31/2025	2	Active	**1**
03	UL Environment	**Expanded Shale, Clay, Slate, and LW Aggregate**	1/25/2022	1/25/2027	2.0	Active	**1**
04	UL Environment	**Concrete Masonry and Segmental Concrete Paving Products**	11/11/2020	11/11/2025	1	Active	**1**
05	UL Environment (current)	**Part B: Steel Construction Products (North America)**	8/26/2020	8/26/2025	–	*Update In development* *(Smart EPD)*	**1**
05	UL Environment	**Part B: Aluminum Construction Products**	2/16/2022	2/16/2027	2	Active	**1**
07	UL Environment	**Part B: Building Envelope Thermal Insulation**	4/11/2018	4/11/2024	–	*Update In development*	**1**
08	NSF International	**NGA Flat Glass PCR v2**	9/2020	9/30/2025	2	Active	**1**
08	UL Environment	**Part B: Processed Glass (North America)**	12/6/2022	12/6/2023		Active	**1**
09	NSF International	**Architectural Coatings**	6/23/2017	6/30/2023	1	Active	**1**
06	UL Environment	**Part B: Structural and Architectural Wood Products**	5/29/2020	10/21/2024	1.1	Active	**2**
07	ASTM	**Single-Ply Roofing Membranes**	10/11/2019	7/17/2024	2	Active	**2**
07	UL Environment	**Part B: Insulated Metal Panels, Metal Composite Panels, and Metal Cladding: Roof and Wall Panels v2.0**	10/23/2018	10/23/2023	2	Active	**2**
07	UL Environment	**Part B: Asphalt Roofing Products**	7/17/2019	7/19/2024		Active	**2**
07	UL Environment	**Part B: Cladding Product Systems**	4/13/2021	4/13/2026		Active	**2**
09	NSF International	**Gypsum Panel Products**	7/17/2019	7/17/2024	1	Active	**2**
09	UL Environment	**Part B: Flooring**	9/28/2018	9/28/2023	2	Active	**2**
09	UL Environment	**Part B: Metal Ceilings and Interior Wall Panel System**	1/15/2020	1/15/2025		Active	**2**
09	UL Environment	**Part B: Non-Metal Ceiling Panels**	4/13/2021	4/13/2026		Active	**2**
32	NAPA	**PCR for Asphalt Mixtures v2.0**	4/1/2022	3/1/2027	2	Active	**2**
32	Smart EPD	**Asphalt Binder**	TBD	TBD	-	In development	**2**

Specifically, the CLF considered the following factors when prioritizing:

- Embodied carbon significance:
  - relates to high-embodied carbon and/or very low-embodied carbon products
  - EPA RFI category tier (1, 2, 3, or none)
  - projected federal projects emissions estimate (# metric tonnes CO_2e).(Tilak et al, 2022)
- PCR currently has limitations to comparability (within or across product types) that a PCR update could address:
  - lack of background data prescriptiveness
  - limitations to determining if products are functionally equivalent, e.g., lack of product technical characteristics reporting requirements
  - allocation conflicts
  - other comparability limitations
  - material-specific vs. material-agnostic? And if material-specific, expandable to material-agnostic?
  - relationship to other priority categories in the supply chain (e.g., cements and aggregates for concretes).

APPENDIX C: SUMMARY OF WORKSHOP FINDINGS

On April 12 and 13, CLF hosted two 90-minute virtual workshops to collect input from 52 individuals from 44 different organizations across the United States and Canada representing perspectives from AEC, manufacturing, LCA practitioners, NGOs, and government agencies.

The workshops focused on three areas that informed this roadmap:

1. **Mapping the LCA ecosystem:** CLF asked participants to provide input on proposed diagrams of the LCA ecosystems for products (EPDs), buildings (WBLCA), and roadways, including key standards, guidelines, data sources, and tools.
2. **Challenges and Solutions Brainstorm**: CLF asked participants to share their perspectives on current challenges to implementing LCA-based policies and brainstorm solutions to overcoming these challenges.
3. **Prioritizing Solutions:** CLF asked participants to prioritize an initial list of solutions provided by CLF, with the option to add solutions identified in the previous activity.

In the first activity on "Mapping the workshop," participants provided feedback on draft diagrams of the data ecosystem. These responses informed the figures and content in Section 2.

In the second activity, workshop participants brainstormed challenges and solutions. These were collected and synthesized by the CLF team and included in Section 3. In the final activity, participants prioritized a list of potential solutions. The results are summarized in Table C1

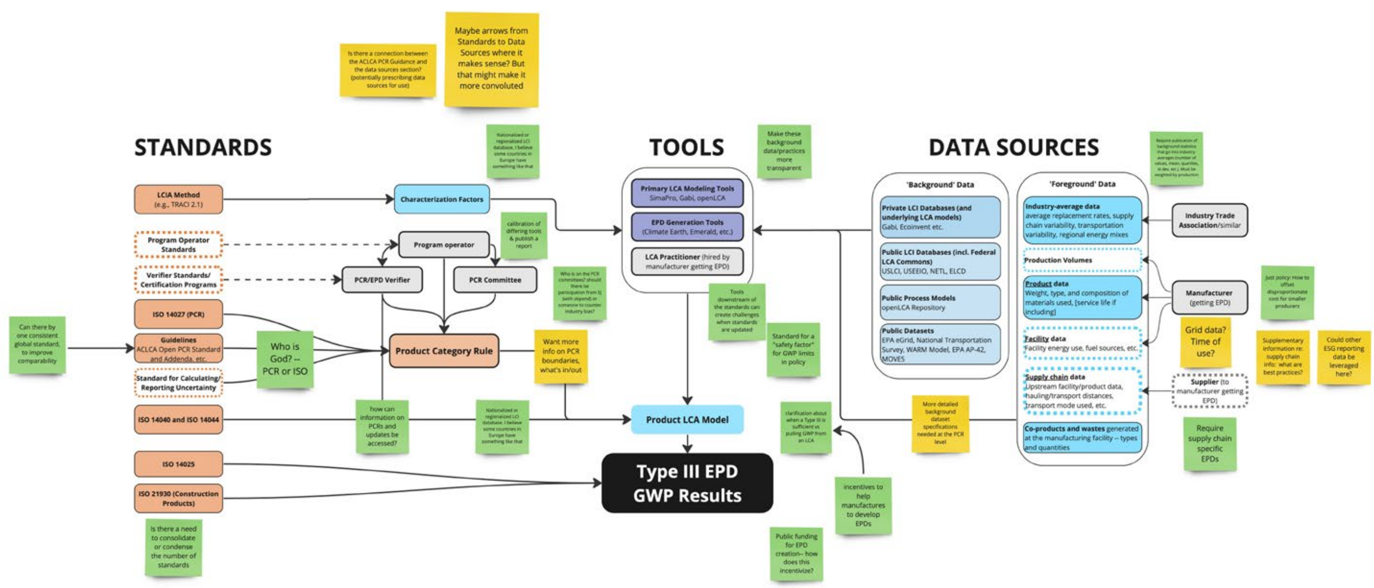

Figure C1 Workshop feedback on "Mapping the EPD data ecosystem for construction products" diagram.

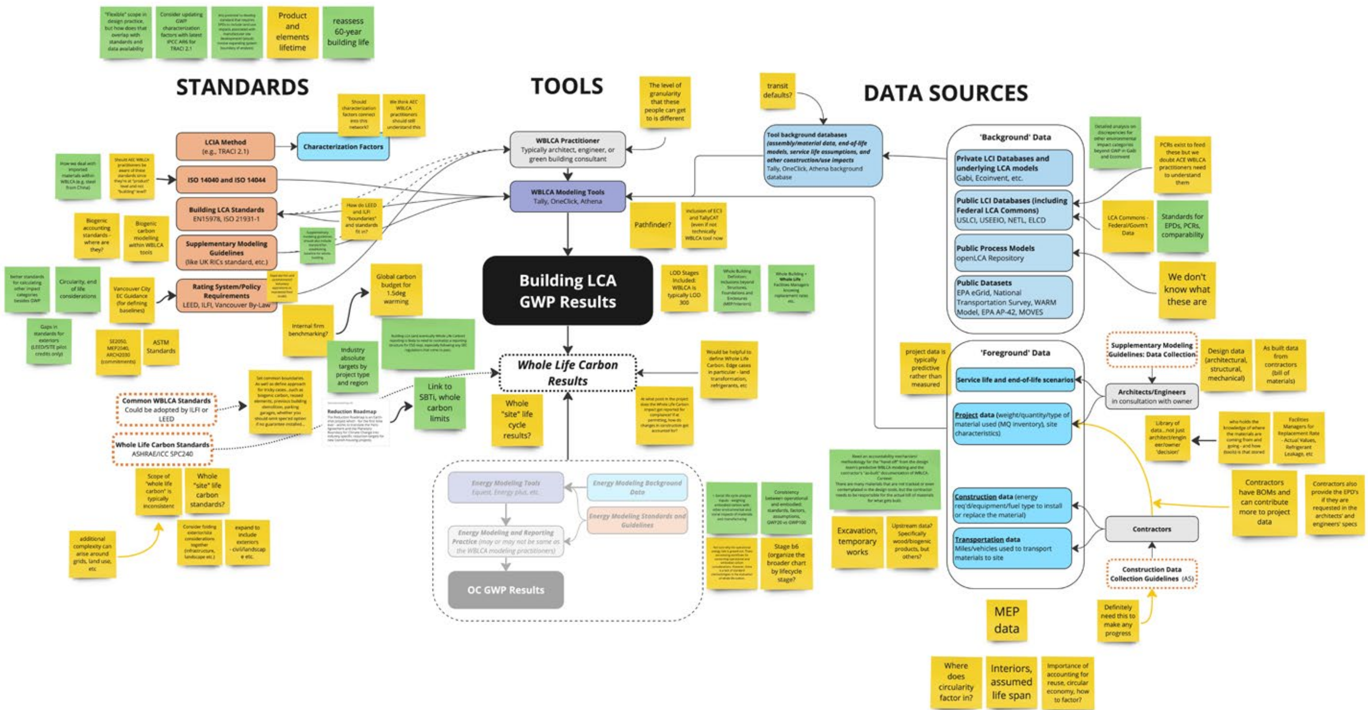

Figure C2 Workshop feedback on "Mapping the building LCA ecosystem" diagram.

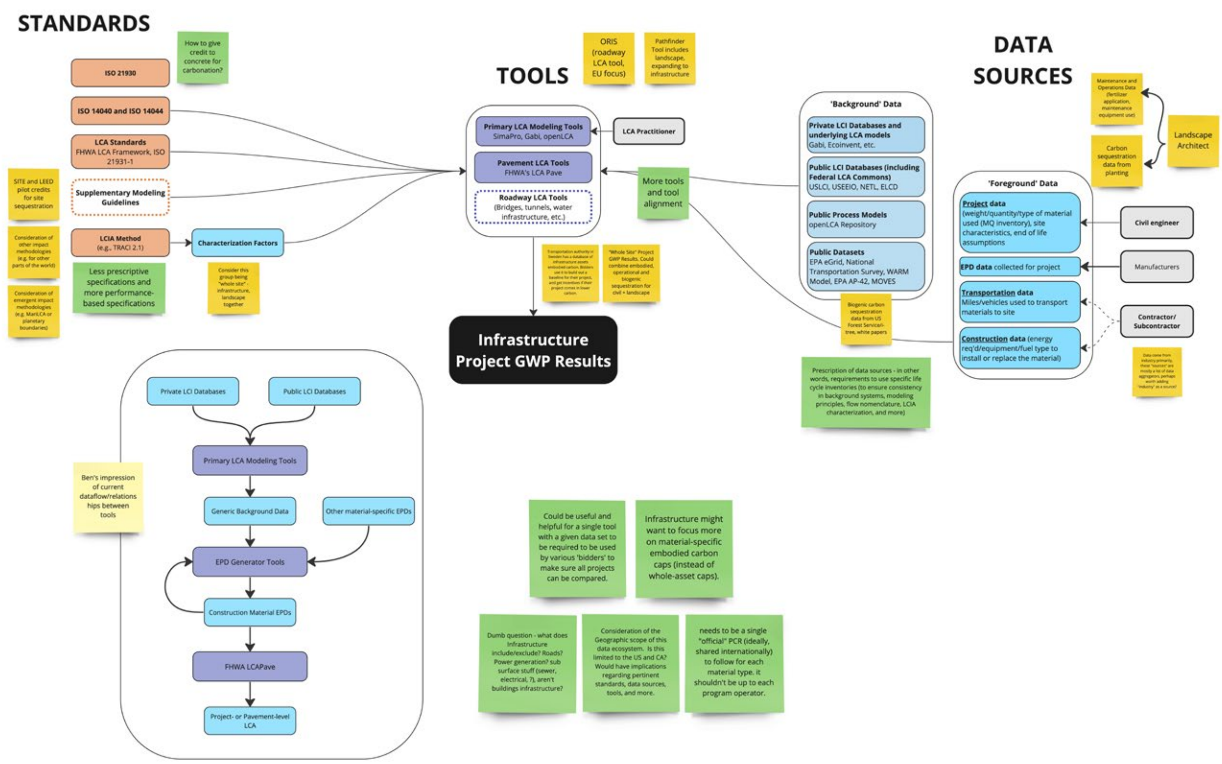

Figure C3 Workshop feedback on "Mapping the roadway LCA ecosystem" diagram.

Table C1 Workshop feedback on prioritizing solutions to advance the LCA ecosystem. Numbers indicate how many groups placed the solution (e.g., “Require facility-specific data”) in each prioritization level (e.g., “Low hanging fruit”). Stars indicate participant emphasis on the solution’s importance.

Solution This text was provided by CLF Team on sticky notes, which the workshop groups were then asked to proriortize	**Starred?**	**Prioritization of Solution**					
		Low hanging fruit	**Key but requires more resources**	**Do it next**	**Do it if/when there's time**	This is already done/Not needed	*# of groups that didn't place this sticky note*
General LCA							
Require project LCA training in architecture/ engineering programs		7.5	2.5	0	1	0	1
More LCA training (practitioners, users, government, etc.)	*	4	0	1	0	0	7
Additional research to inform stages B-C		1	4	1	1	0	5
Increase access to transparent, high quality public data	*	1	4	1	0	0	6
Update TRACI		0.5	1.5	1	1	0	8
National method for calculating carbon-storage GWP benefits		0	7	2	0	0	3
Increase global standards alignment (ISO/EN)		0	3	1.5	0.5	1	6
Create tools to help industry share data confidentially		0	2	2	1	0	7
Improve interoperability between LCI datasets/LCA tools		0	1	4	1	0	6
Fill data gaps: alternative materials/ technologies		0	0	3	1	0	8
Product LCA							
Require supply-chain-specific upstream data for big impacts (cement, asphalt binder, steel mills, etc)		4	5	1	1	0	1
Improve EPD verification process		4	0	2	1	0	5
Create Program Operator requirements		4	0	0	0	1	7
Require facility-specific data		3.5	3	1	1.5	0	3
Make EPD generation faster and cheaper for manufacturers (tools/other)		2.5	8.5	0	0	0	1
PCRs require same background datasets (within PCR) > comparable EPDs	*	2	5	1	0	0	3
Require open source LCA template models as part of PCR creation		1	2	1	0	0	8
Expand PCRs to cover bio-based/other alternative materials		0	7	2	0	0	3
Harmonize across PCRs > EPDs can be data source for project LCAs	*	0	7	1	0	0	4
Make EPDs cradle-to-grave (A-C)		0	2	1.5	2.5	0	6
Project LCA (Buildings and Roadways)							
Identify prescriptive EC reduction strategies for codes/ certifications that don't require modeling		8	0	1	0	0	3
Create a central reporting database for project LCA results		5	1.5	2.5	1	0	2
Increase policy incentives/ requirements to do project LCA	*	4	6	1	0	0	1
Develop a nationally standardized LCA method and modeling guidelines for practitioners	*	4	5	3	0	0	1
Create a central reporting database for material quantities		4	4	0.5	0.5	0	2
Establish national benchmarks for different project types	*	1	7	1	1	0	2
Work with LCA tool developers to align software with national LCA method	*	1	6	3	1	0	1
Create a verification process for project LCA results	*	1	3	3	2	0	4
Set total carbon budgets for buildings that align with global climate targets		0	1	6	1	0	4