ADVANCING STANDARDS
TRANSFORMING MARKETS

Workshop on Decarbonization

A GAP ANALYSIS OF LCA STANDARDS FOR INDUSTRY

Noah Last
Circular Economy Program, National Institute of Standards and Technology

Amy Costello
Armstrong World Industries, Inc

KC Morris
Systems Integration Division, National Institute of Standards and Technology

Joshua Kneifel
Applied Economics Office, National Institute of Standards and Technology

Catherine Houska
Catherine Houska Consulting, LLC

Helping Our World Work Better®

Contents

Executive Summary

ASTM International's committee on sustainability (E60), in collaboration with the National Institute of Standards and Technology (NIST), hosted the virtual "Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry" on October 10-11, 2023. The event convened approximately 150 stakeholders from across industry, government, non-government organizations (NGOs), and academia to discuss the challenges and opportunities that industry faces in applying life-cycle assessment (LCA) to address decarbonization efforts. The workshop aimed to identify and map gaps in international standards related to industrial decarbonization with a focus on LCA and identify opportunities for standards to address these gaps.

This report summarizes the outcomes from the workshop and is valuable to those applying LCA to improve their organization's sustainability practices. Sustainability managers and practitioners will find a collection of existing standards and best practices for using LCA tools, data repositories, methods for allocating environmental impact to products, and problems that exist in using them, particularly for decarbonization efforts. Procurement professionals and other consumers will benefit from understanding the current limitations of the LCA approach. This report will be valuable to standards development organizations (SDOs) and other standards professionals as it will inform future planning. Finally, experts interested in creating new standards and adapting existing ones will find gaps in the field of LCA and suggestions for overcoming these gaps.

LCA is a powerful tool for quantifying the environmental impacts of a product or service throughout its life cycle and is being applied in an ever-growing number of applications, with particular interest in life-cycle carbon emissions. However, the same factors that make LCA so powerful also make it difficult, namely its complexity. An LCA requires appropriate, robust, trusted life-cycle data; insight into the potential wide variation in the use and eventual fate of the product or service; and knowledge for interpreting and applying the complex rules for completing LCA studies. The resulting LCA reports then must be appropriately understood to make informed decisions. Thus, experts are needed who can navigate LCA tools in light of these challenges.

An LCA report is generated based on a series of methodology standards combined with a variety of datasets and tools (both publicly and commercially available); practitioners and third-party verifiers combine expert understanding of LCA methods, data availability and selection, and professional judgement to develop and interpret LCA results used in product comparisons. Each of these aspects of the LCA process provides challenges and opportunities that must be addressed. These challenges can include: vague language in existing standards; scattered and sparse data; incomplete or inconsistent LCA modeling and review; or inappropriate interpretation of the results.

While LCA tracks multiple impacts—from smog to eutrophication to renewable and non-renewable resource consumption—organizations and governments are increasingly

Executive Summary

leveraging it to support decarbonization goals. In addition, LCA is used to create environmental product declarations (EPDs), often described as “nutritional labels” that consumers can use to determine the environmental impacts of the products they purchase. LCAs and EPDs satisfy two major national emissions-reduction needs: to quantify the impacts of decarbonization actions and to measure progress towards decarbonization goals. However, while a portfolio of standards for LCA (e.g., ISO 14040 and 14044), EPD (e.g., ISO 14025), and carbon accounting (e.g., Greenhouse Gas Protocol; ISO 14064) exist, problems related to completeness, comparability, transparency, and accuracy are emerging as practitioners apply LCA methods and tools to generate EPDs for an ever-wider array of products and services.

The ASTM Workshop on Decarbonization focused on three challenges related to LCA and EPD standards

1. Current LCA methods rely heavily on interpretation;
2. Robust, comparable data is often difficult to gather; and
3. The use and end-of-use stages of the product life cycle are important for measuring all the carbon emissions associated with a product or service but can be difficult to integrate into the LCA methodology.

New standards and updates to existing standards are needed to resolve these challenges.

This report discusses the above challenges and the insights generated from the workshop, with particular emphasis on standards that ASTM and other consensus standards bodies may pursue to better support the world’s decarbonization efforts. The report concludes with categories of voluntary consensus standards needed to strengthen LCA as a rigorous tool for decarbonization. It should be noted that some of these challenges and suggestions for standards are not restricted to carbon emissions and also apply to resource consumption (e.g., energy, water) or other environmental impacts (e.g., ozone depletion, criteria air pollutants).

The workshop led to some initial success in promoting new standards in this critical area. Since the workshop, two draft ASTM standards have been introduced to integrate elements of the use and end-of-use stages of the built environment into LCA: The practice for minimum criteria for comparing materials and systems during built environment use stage life cycle assessments (LCA) (WK90102); and the standard practice for preparing an environmental and human exposure screening report (ESR) for substances used in the built environment (WK90146). However, additional efforts are needed.

Interested parties applying LCA in their decarbonization strategies should be aware of these challenges. As they assess the challenges, they should identify how standards can help move their efforts forward. The standards identified here reflect shared interests with other stakeholders. Individuals and organizations from the broader stakeholder community are needed to work with standards bodies such as ASTM to reach consensus and produce new standards in these critical areas.

Figures

Tables

Acronyms

ACLCA	American Center for Life Cycle Assessment
AEO	Annual Energy Outlook
ANL	Argonne National Laboratory
ASTM	ASTM International (formerly American Society for Testing Materials)
CAMPD	Clean Air Markets Program Data
CED	Cumulative Energy Demand
CORRIM	Consortium for Research on Renewable Industrial Materials
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EGRID	Emissions & Generation Resource Integrated Database
EIA	Energy Information Administration
EOU	End of use
EPA	U.S. Environmental Protection Agency
EPD	Environmental product declaration
ERG	Eastern Research Group, Inc.
FEDEFL	Federal Elementary Flow List
FHWA	U.S. Federal Highway Administration
GHG	Greenhouse gas
GHGI	Greenhouse gas inventory
GHGRP	Greenhouse gas Reporting Program
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies
GWP	Global warming potential
ILCD	International Life Cycle Data System
ISO	International Organization for Standardization
JSON-LD	JavaScript Object Notation for Linked Data
LCA	Life cycle assessment
MOVES	MOtor Vehicle Emission Simulator
NETL	National Energy Technology Laboratory
NGO	Non-governmental organization
NIST	U.S. National Institute of Standards and Technology
NOAA	U.S. National Oceanic and Atmospheric Administration
NREL	National Renewable Energy Laboratory
PADD	Petroleum Administration for Defense District
PCR	Product category rule
TRACI	Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts
USDA	U.S. Department of Agriculture
USEEIO	U.S. Environmentally-Extended Input-Output
USFS	U.S. Forest Service
USGBC	U.S. Green Building Council
USLCI	U.S. Life Cycle Inventory

i. Introduction

ASTM International's committee on sustainability (E60) in collaboration with the National Institute of Standards and Technology (NIST) hosted the virtual "Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry" on October 10-11, 2023. The workshop aimed to a) identify and map gaps in international standards related to industrial decarbonization with a focus on life-cycle assessment and b) understand how ASTM International can assist in addressing these gaps. (Note that in this report decarbonization refers to the reduction and elimination of greenhouse gas (GHG) emissions, otherwise referred to as carbon emissions or the carbon footprint.)

The workshop convened approximately 150 stakeholders from across industry, government, non-government organizations (NGOs), and academia to discuss these challenges and opportunities and included 20 expert presentations across four sessions which structured the engagement

Session 1: Existing & Emerging LCA Standards
Session 2: Better Data for Better Results
Session 3: Carbon Footprints, Baselines, and Reporting
Session 4: Beyond the Gate

The complete agenda and list of presenters is available in Appendix A.

This report analyzes the presentations from the workshop along with polls and comments from audience members, outlines the gaps identified, and presents a summarized list of standards opportunities. Section 2 of the report introduces the role of LCA in decarbonization and ways in which it is currently being applied. Section 3 reviews the existing and emerging LCA standards and guidance related to decarbonization from organizations such as the Greenhouse Gas Protocol (GHG Protocol), International Organization for Standardization (ISO), ASTM International, and the American Center for Life Cycle Assessment (ACLCA). Standards gaps, opportunities for ASTM to fill those gaps, and collaboration opportunities are also considered. Section 4 delves into LCA modeling and data-set needs to support decarbonization and identifies current activities to address these needs. Finally, Session 5 explores the needs and challenges for incorporating the impacts of the use and recovery of products in environmental assessments. These life-cycle stages "beyond the gate" are often overlooked in product LCAs due to the high level of uncertainty in predicting their impacts and a perceived lack of agency by the producers, yet they are especially important for reducing the overall impacts of the products. An increasing global emphasis on a circular economy[1] will enable better recovery of products and materials, thereby enabling an opportunity to reduce the impacts across all the life-cycle stages. A list of existing LCA standards mentioned during the workshop is also included in Appendix B and C. The report concludes with a list of standards needs identified in the workshop and roles for ASTM International to support their development.

1 A circular economy aims to keep materials in the economy and out of landfills and the environment through value-retention processes like reuse, refurbishment, and recycling with a goal of reducing carbon emissions through more efficient use of resources.

ii. Background

This section provides background on work being done to decarbonize the global economy; how governments and organizations are using LCA, product category rules (PCRs), and environmental product declarations (EPDs) to decarbonize; and the persisting challenges in using LCA that motivated the ASTM workshop on decarbonization.

2.1 DECARBONIZATION

Scientific consensus is that humans should reduce GHG emissions entering the atmosphere to reduce the impacts of the earth's changing climate (IPCC, 2018, 2023). Many governments are responding with new policies and regulations, and organizations from across industry are responding with decarbonizing efforts in their operations and the items they produce. A central challenge to these efforts is to identify sources of GHG emissions and develop methods to reliably measure, report, and reduce them. Measurements are needed to identify high-impact activities, establish baselines, and verify and track progress toward decarbonization goals. Interest in carbon accounting, a method by which organizations can report on their carbon emissions, is being fueled by international agreements (e.g., the Paris Agreement) and the new value streams for decarbonization solutions that are emerging worldwide (Ellen MacArthur Foundation, 2024; Hapuwatte et al., 2023; Michaelowa et al., 2019; WBCSD & WRI, 2004).

The 2015 Paris Agreement requires that signatory countries create plans for how they will decarbonize through nationally determined contributions (NDCs) and update those plans every five years. In 2018, an Intergovernmental Panel on Climate Change (IPCC) report found that to maintain the Paris Agreement's goal of less than 1.5°C of global warming by 2100 compared to pre-industrial levels, the world needed to decrease emissions by 45% by 2030 and 100% by 2050 compared to 2010 numbers (IPCC, 2018). This prompted some countries to strengthen their NDCs and a coalition of private organizations with $130 trillion in private capital to create decarbonization goals at COP26 (GFANZ, 2021). These resolutions are triggering an assortment of voluntary and mandatory mechanisms for measuring and reporting GHG emissions at various levels in the ecosystem of production—product, facility, corporate, and whole-country (Climate Leadership ouncil, 2023).

In response, recent and upcoming regulations around the world are seeking disclosure from the private sector for their GHG emissions. The GHG Protocol identifies three scopes for emissions accounting and maintains standards for each scope (see Section 3.2.2.1). In the U.S., the Securities and Exchange Commission (SEC) finalized a rule in 2024 that will require publicly-traded companies to disclose their climate-related risks to the SEC and their investors, including direct emissions from processes (including fuel combustion) and fugitive emissions (Scope 1), and indirect emissions from electricity consumption (Scope 2) (U.S. Securities and Exchange Commission, 2024). In addition, California passed SB 253 (The Climate Corporate Data Accountability Act) in September 2023, which requires that businesses operating in the state with over $1 billion USD in annual revenue report their Scope 1, 2, and 3 emissions (Climate Corporate Data Accountability Act, 2023). The European Union passed a similar disclosure act, the Corporate Sustainability Reporting Directive (CSRD), in 2022 (Council of the European Union, 2022), which requires broad disclosure of the environmental and social impacts from companies operating in the EU (Directorate-General for Financial Stability, Financial Services and Capital Markets Union,

ii. Background

2023). Canada (OSFI, 2023), Brazil (Segal, 2023), the United Kingdom (Deloitte, 2022), and other countries are also beginning to require climate-related risk disclosures for various institutions.

Because of the regulatory actions and the sense of urgency surrounding carbonization, the world is rushing to find solutions and look for ways to identify, account for, and value the sources of GHG emissions and avoidance mechanisms.

2.2 THE ROLE OF LCA IN DECARBONIZATION

Before decarbonization became a priority, significant efforts were underway to improve the "sustainability" of products and systems. The impact-assessment techniques for these efforts ranged from attributional analysis to complex techno-economic analyses. But as product sustainability efforts evolved, so too did the desire to quantify and compare the life-cycle sustainability impacts between products.

A key tool for evaluating and quantifying product environmental impacts is LCA (ISO, 2006b, 2022). LCA is a methodology to quantify mass and energy flows (e.g., materials, water, electricity) associated with the life cycle of a product, service, or manufacturing process (hereafter referred to as "processes") and calculate the potential environmental impacts (e.g., emissions) associated with these flows (hereafter "elementary flows"). An LCA model uses foreground (i.e., primary) data directly collected about the processes, such as the quantity of electricity used, in combination with background (i.e., secondary) data on the associated elementary flows, such as the carbon dioxide (CO_2) emissions from the generation and consumption of a unit of electricity. As shown in Figure 1, all elementary flows in an LCA model are summed to get an inventory of quantities for each, which is called a life-cycle inventory (LCI). These calculations rely on one or more databases that provide estimated elementary flows for a wide range of processes throughout the life cycle, from resource extraction through manufacturing and use through end-of-life processing. These databases are referred to as background LCI databases.

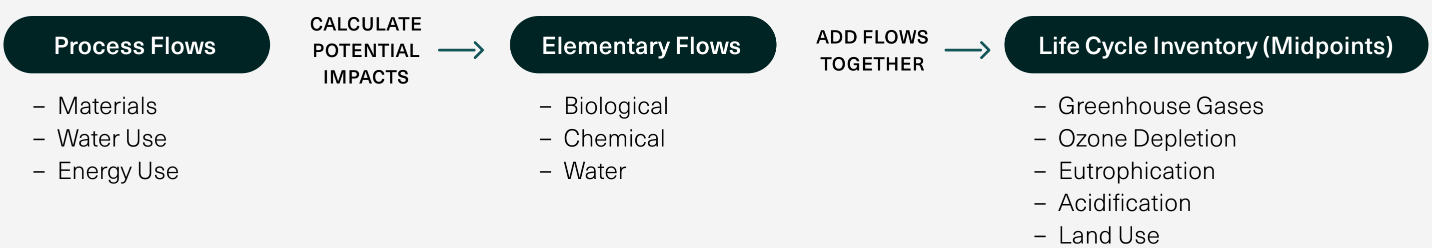


Figure 1 — An LCA study compiles the flow of resources across the life cycle of a product or service and adds the flows together to create a life cycle inventory.

LCA is a complex process that is made more manageable through the use of different types of data-aggregation techniques. To allow for interpretation of the large inventory of elementary flow quantities, these flows are aggregated into what are called impact categories (e.g., ozone depletion, water use). Each impact category has a reference flow that serves as the base unit to which all relevant elementary flows are converted based on conversion factors specified in the selected impact calculation methodology (i.e.,

ii. Background

impact method). These impact category-level results are referred to as life-cycle impact assessments (LCIAs). Numerous and diverse impact methods are available depending on the LCA application and modeler preferences. In practice, this leads to great diversity in the data that supports LCAs, complicating the comparison of results. LCI data and LCIA impact methods are discussed further in Section 4.

Among the indicators that an LCIA may include is global warming potential (GWP), which is used to estimate the GHG emissions (e.g., CO2, methane, nitrous oxide) associated with a product or service. Producers of products can use LCA to identify hotspots within their businesses with high environmental impacts as targets for improvement or to compare alternative product designs and business strategies for minimizing environmental impacts. Externally, businesses use LCA for marketing and communication of their environmental efforts and impacts (ACLCA, 2023).

Although LCA as a tool has existed for decades, its prevalence and acceptance has grown significantly over the last decade. A key driver of increased interest and acceptance of LCA is the inclusion of LCA-related credits in green building credit rating systems. For example, the U.S. Green Building Council (USGBC) included LCA-related credits in the LEED v4.0 rating system in 2013, leveraging environmental product declarations (EPDs) that use LCA to report quantitative environmental impact performance. LCA-related credits are also expected for LEED v5.0.

EPDs serve as a tool for communicating the findings of LCAs. According to ISO 14025, EPDs (also known as “type III environmental declarations”) “present quantified environmental information on the life cycle of a product to enable comparisons between products fulfilling the same function” (ISO, 2006a). EPDs, and the LCA reported within, follow product category rules (PCRs) that have been established for specific product types or categories. PCRs attempt to level the playing field by establishing key assumptions that EPD developers and LCA modelers must follow, including required assumptions in the absence of actual data (e.g., percent of waste to landfill versus incineration). EPDs can be designed such that buyers can compare the environmental performance of multiple products/services with the same function, so it is key that for comparison purposes, each evaluation uses the same PCR for their product type. Figure 2 details the relationships among LCA, PCR, and EPD. Per ISO 14025, if the PCRs used to develop the EPD are not the same, then the EPDs have limited comparability. However, it should be noted that the use of the same PCR is a necessary but not sufficient condition for comparability due to variations in factors such as underlying assumptions and data sources, which are discussed further in Section 4.

In principle the method is sound, and in practice it works relatively well under specific conditions. Comparisons must be based on the same reporting guidance (i.e., the same PCR or LCA model), the same methods (e.g., allocation), assumptions, data, and modeling tools. These assumptions can often be met by a producer in comparing their design and business strategy options. However, environmental variables are not always consistent

ii. Background

between EPDs, making it difficult for consumers to compare products from different business lines (e.g., manufacturers, material types, and geographies). LCAs also depend on underlying datasets or input resources (e.g., materials), but the necessary datasets may not exist, may be inconsistent with one another, or may not be representative of underlying conditions for the specific product (e.g., different localities). Finally, different LCA tools may use different datasets or differ in how these data are aggregated into a final evaluation, resulting in inconsistent results. This workshop aimed to identify ways in which these variables can be normalized using standards such that consumers can rely on LCAs to better compare products

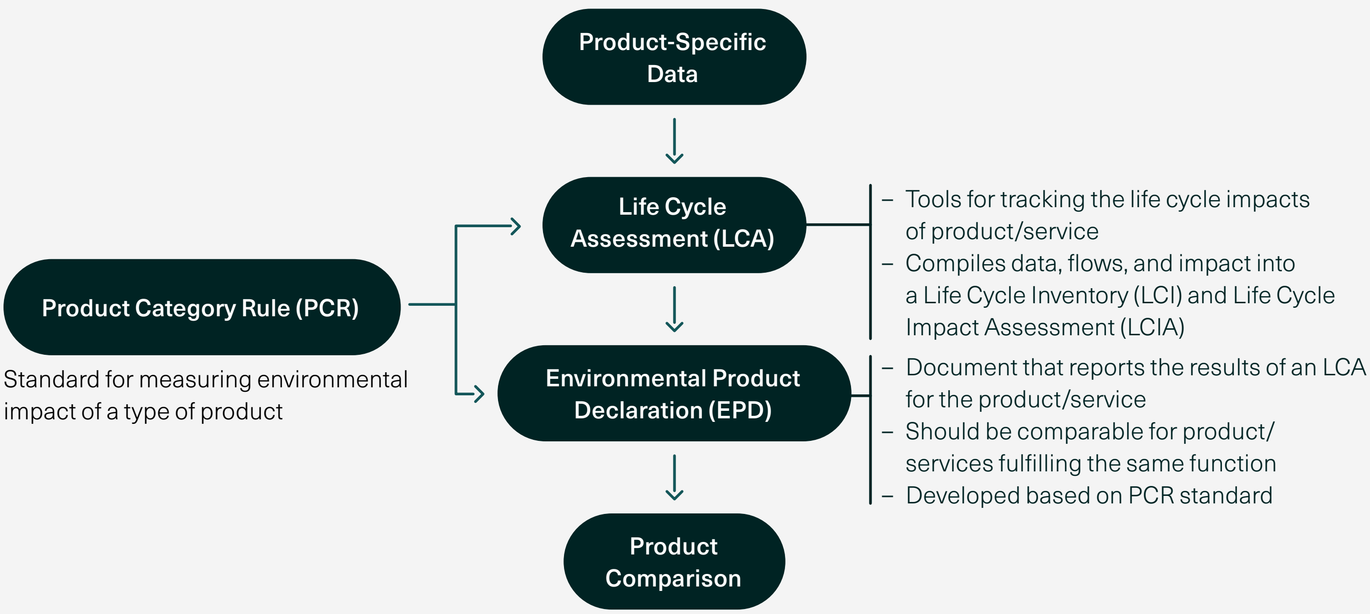


Figure 2 — A high-level view of how consumers use data, LCA, and EPDs to identify low carbon products and services. The PCR defines the product-type-specific standard for selecting the data, performing the LCA, and filling out the EPD. See Figure 1 for information about LCI.

2.3 DEMAND FOR ENVIRONMENTAL PRODUCT DECLARATIONS

Demand is growing for products to report their associated life-cycle environmental impacts. Part of this demand is fueled by organizations' desires to procure goods and services with lower associated carbon emissions to reach sustainability goals, such as GHG emissions reductions. At the corporate level, capital goods and purchased goods and services are accounted for as part of a company's Scope 3 emissions (Figure 3). (See Section 3.2.2.1 for information on the scopes of emissions.) Companies have begun to use EPDs as a means to report the emissions associated with the products and services they purchase and find alternative products and services with lower carbon footprints.

ii. Background

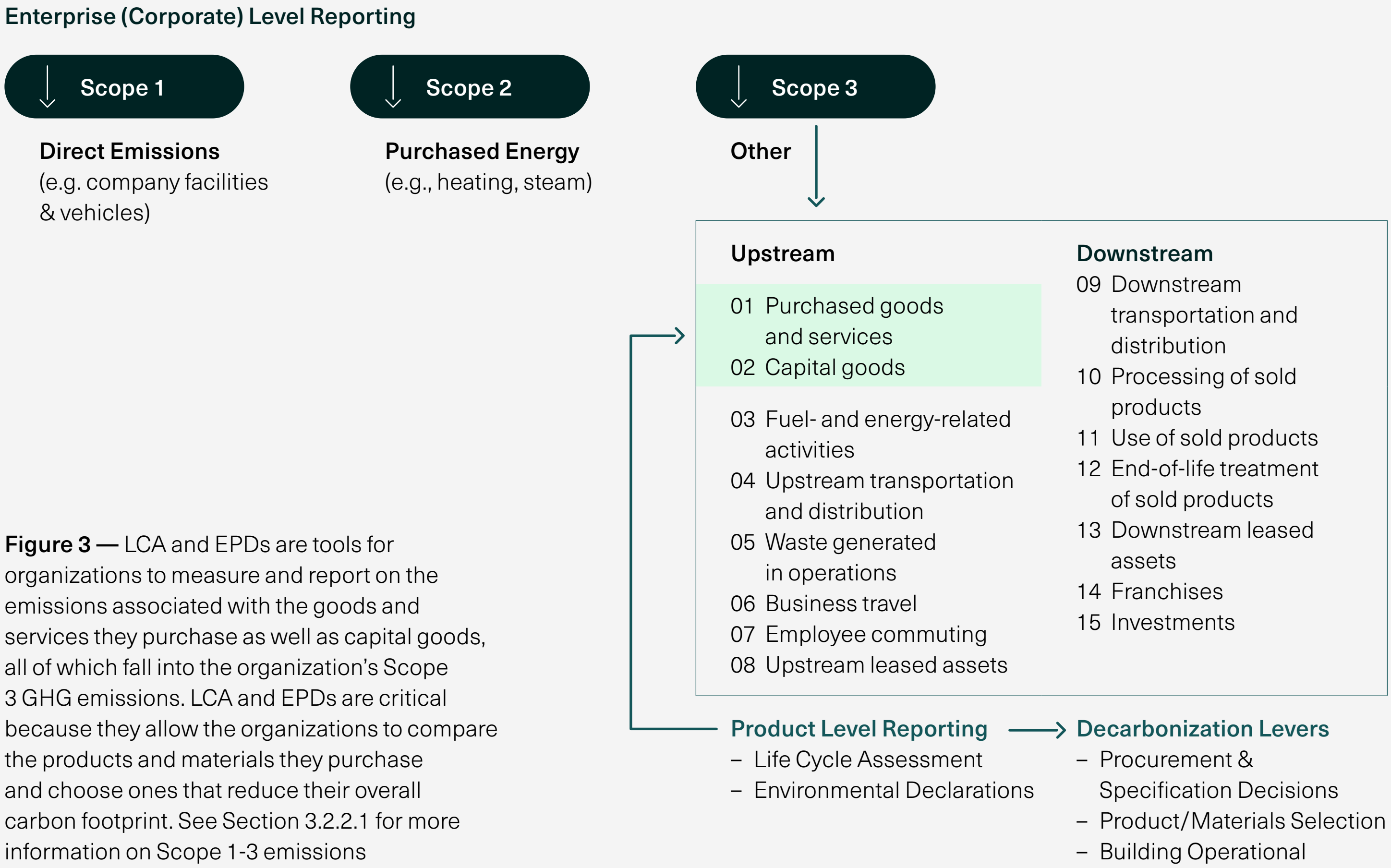


Figure 3 — LCA and EPDs are tools for organizations to measure and report on the emissions associated with the goods and services they purchase as well as capital goods, all of which fall into the organization's Scope 3 GHG emissions. LCA and EPDs are critical because they allow the organizations to compare the products and materials they purchase and choose ones that reduce their overall carbon footprint. See Section 3.2.2.1 for more information on Scope 1-3 emissions

In the U.S., several initiatives use EPDs and LCA to track progress towards the country's Paris Agreement goals, including buy clean initiatives through which states and the federal government prioritize buying low-carbon materials for construction projects. The federal government implemented the Federal Buy Clean Initiative in 2021, which uses EPDs to identify low-carbon materials for federal procurement. This includes materials purchased directly by the federal government and by its contractors and subcontractors for construction projects receiving federal funding (Council on Environmental Quality, 2022; Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability, 2021; Office of the Federal Chief Sustainability Officer, 2023). As of 2023, the Buy Clean Initiative also partners with 13 U.S. states[2] that adopt the low carbon procurement standards for construction projects receiving state funds (The White House, 2023). Four of those states have passed their own Buy Clean laws (Figure 4).

2 California, Colorado, Hawaii, Illinois, Maine, Maryland, Massachusetts, Michigan, Minnesota, New Jersey, New York, Oregon, and Washington.

ii. Background

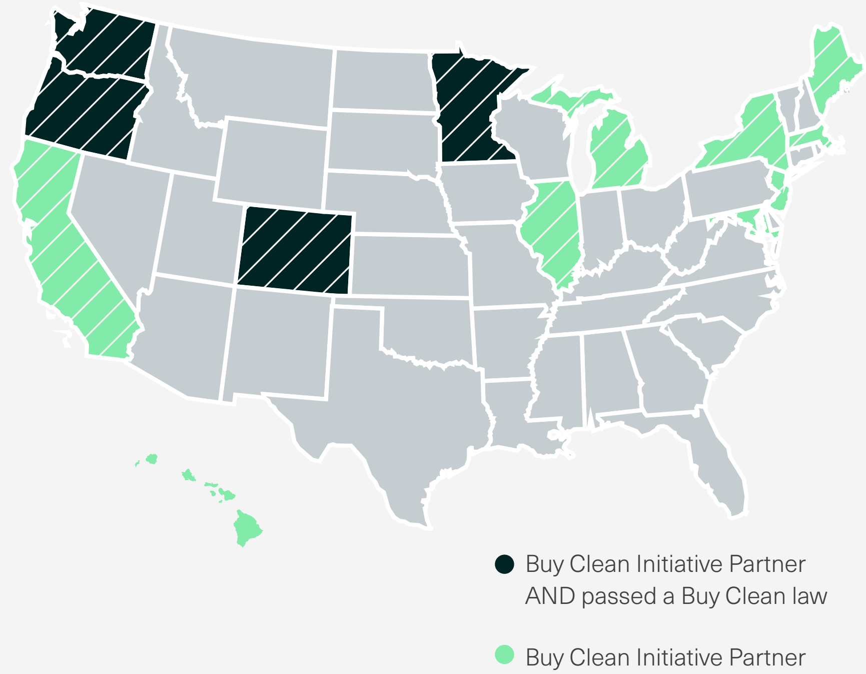


Figure 4 — Map of the 13 U.S. states that have partnered with the Federal Buy Clean Initiative and the four states that have passed buy clean legislation as of 2023.

Another effort is the Federal Highway Administration's (FHWA's) Climate Challenge, which is funding 25 state departments of transportation (DOTs) to use EPDs when considering pavement materials and designs to use. The FHWA also provides training and works with industry and academia to identify pavements that have lower-emissions and are more resilient (more resilient materials generally have a longer life, reducing the frequency of maintenance and replacement). The goal of this program is to get state DOTs to better measure their emissions impacts and prioritize more sustainable materials (FHWA, 2022a, 2022b).

The 2022 Inflation Reduction Act directs the U.S. Environmental Protection Agency (EPA), Department of Housing and Urban Development (HUD), General Services Administration (GSA), and Federal Emergency Management Agency (FEMA) to also fund projects to support low emissions and embodied carbon materials based on EPDs. To support this effort, the EPA has received funding to create a low carbon labeling program and a grant program to fund projects to support EPD quality improvements in the following areas:

- EPD development.
- Robust data for EPDs.
- Robust PCR Standard Development, PCRs, and Associated Conformity Assessment Systems.
- Robust tools and resources to support and incentivize development and verification of EPDs.
- Robust EPD data platforms and integration.

ii. Background

At the workshop, the EPA announced a new grant program on Reducing Embodied Greenhouse Gas Emissions for Construction Materials and Products. The program will support businesses and organizations in developing EPDs and PCRs for the construction and building industries (US EPA, 2023). Subsequently, funding was awarded in 2024 to standards development efforts broadly and for specific product types; for example, ACLCA will use funding to enhance EPD standardization across sectors by updating their PCR Guidance and PCR repository; Global Bamboo Technologies, Inc. will also develop industry consensus on calculating biogenic carbon in EPDs, then integrate that into ACLCA's PCR Open Standard. The grant also gives money to organizations to conduct LCAs and for workforce development.

2.4 CHALLENGES

The broadening adoption of LCA-based tools, including EPDs, for decarbonization efforts has exposed gaps, inconsistencies, and other issues in LCA, PCRs, and EPDs. Table 1 provides areas of variation and non-uniformity, presented by the EPA at the workshop, that make it difficult to confidently measure and compare the impacts of products and processes, a major bottleneck to making optimal decarbonization decisions (Macri, 2023).

Table 1 — Examples of challenges identified by the U.S. EPA that practitioners are facing when creating and using PCRs and EPDs (Macri, 2023).

PCRs	**TOO MUCH VARIATION**	– Specific background datasets. – Methods for primary data collection. – Access to underlying LCA. – Background of stakeholders in the development. – Methods for addressing data quality. – Harmonization with upstream and downstream PCRs. – Granularity of unit processes.
EPDs	**TOO MUCH VARIATION**	– LCA and EPD generation tools/consultants. – Names, years, and sources of background datasets. – Whether supply chain data are manufacturer vs. facility specific. – Uncertainty of results. – Consistency between modeling software and versions.
	LACK OF UNIFORMITY	– Format. – Scope. – Nomenclature of EPD types (e.g., manufacturer, facility-specific). – Prescriptiveness. – Others.

ii. Background

Table 2 — List of U.S. Program Operators that manage PCRs as of June 3, 2024.

PROGRAM OPERATOR	PCRs MANAGED
ASTM INTERNATIONAL	4
FPINNOVATIONS	1
LABELING SUSTAINABILITY / P3 OPTIMA	1
NAPA	3
NSF	16
NSF / ASTM	10
SMART EPD	13
SUSTAINABLE MINDS	12
UL ENVIRONMENT	41
TOTAL PCRS	101

A factor that leads to some of these challenges is the decentralized nature of PCR and EPD development. Instead of a single entity overseeing the development of all PCRs, numerous program operators (POs) manage the PCR development process for specific product categories (Table 2). In the U.S., numerous POs exist. Most POs are members of the Program Operator Consortium that includes:

- ASTM International.
- CSA Group.
- FPInnovations.
- National Asphalt Pavement Association (NAPA).
- NSF International.
- National Ready Mixed Concrete Association (NRMCA).
- P3 Optima.
- SCS Global Services.
- Smart EPD.
- Sustainable Minds.
- Underwriters Laboratories (UL) Environment.

There are currently 101 total PCRs that are active (88) or under development (13) in the U.S. through a largely "one-off" approach where decisions are made at the PCR committee level. Of the 88 active PCRs, 25 expire between June 2024 and December 2024 and require an updated release.

Voluntary consensus standards are a means to address these challenges. The standards development process brings together LCA experts, practitioners, and policymakers to create consensus on language and guidelines for creating more uniformity in areas such as PCR and EPD definitions, enabling comparability of the resulting declarations. Standards are critical because they are created by stakeholders who collaborate to create consensus around the methods and materials that work best for their industry. Once developed, these can be written into contracts and industry code adoption, allowing them to be incorporated into federal and state laws and policies (e.g., buy clean initiatives).

iii. Standards for Products and Materials Carbon Assessment

This section reviews standards organizations that play a role in decarbonization and provides detailed information about some pertinent standards related to LCA, carbon accounting, and carbon allocation.

3.1. STANDARDS DEVELOPMENT ORGANIZATIONS

The workshop discussed the landscape of existing LCA and carbon accounting standards, with the goal of identifying gaps that ASTM or other organizations may fill. With a global issue like decarbonization, the need for robust, consensus-based standards becomes more important, especially to entities that conduct business in multiple countries. Two levels of SDOs address these needs:

1 International consensus-based standards that meet the World Trade Organization's (WTO) "Six Principles for the Development of International Standards, Guides, and Recommendations" (Figure 5).
2 Member-supported organizations that develop standards. These standards may or may not be accredited by a national or regional SDO such as the American National Standards Institute (ANSI) in the U.S.

Figure 5 — The World Trade Organization's Six Principles for the Development of International Standards, Guides and Recommendations (WTO, 2000).

3.1.1. INTERNATIONAL STANDARDS BODIES THAT MEET THE WTO'S REQUIREMENTS

ASTM International and ISO are two organizations that meet the rigorous requirements of the WTO's Six Principles (WTO, 2000). Information about both organizations is detailed in the sections below along with a synopsis of standards that each develop and their contributions to decarbonization. Additional details about these standards can be found in Section 3.2. In addition, a full list of standards discussed during the workshop are in Appendix B and C.

3.1.1.1. ASTM INTERNATIONAL

ASTM International develops voluntary, consensus-based standards. They are developed by its members, who represent a range of organizations and entities. The organization

iii. Standards for Products and Materials Carbon Assessment

consists of over 100 technical committees through which individual members participate in the standards development process. A technical committee consists of a main committee and several subcommittees. The subcommittees create task groups that shepherd the development of specific standards. While the standards are developed through collaboration among individual technical experts, each ASTM member organization receives one vote towards approving final standards for publication. In general, ASTM develops six types of standards (ASTM International, 2021b):

1 **Terminology:** a document comprising definitions of terms; explanations of symbols, abbreviations, or acronyms.
2 **Guide:** a compendium of information or series of options that does not recommend a specific course of action.
3 **Practice:** a set of instructions for performing one or more specific operations that does not produce a test result.
4 **Classification:** a systematic arrangement or division of materials, products, systems, or services into groups based on similar characteristics such as origin, composition, properties, or use.
5 **Specification:** an explicit set of requirements to be satisfied by a material, product, system, or service.
6 **Test method:** a definitive procedure that produces a test result.

The committee on sustainability has developed the following LCA-related standards:
- **Practice E2921** for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with Building Codes, Standards, and Rating Systems
- **Guide E3027** for Making Sustainability-related Chemical Selection Decisions in the Life-Cycle of Products
- **Guide E3199** for Alternative Allocation Approaches to Modeling Input and Output Flows of Secondary Materials and Related Recycling Scenarios in Life Cycle Assessment
- **Guide E3341** for general principles of resilience

3.1.1.2. INTERNATIONAL ORGANIZATION FOR STANDARDIZATION (ISO)

ISO is an international standards body that develops consensus standards through its national standards bodies. Each national standards body represents the interests of a single country, and each country gets one vote. ISO standards foster coordination that supports various domains including international trade, diplomacy, and environmental management.

ISO's work is organized through technical committees (TCs) and subcommittees (SCs). Both focus on specific topics and bring together experts and representatives from different countries. Their collective efforts result in the creation of standards that benefit industries, governments, and society at large.

From an environmental perspective, ISO TC 207 on Environmental Management, SC 5 on Lifecycle Assessment has developed key standards related to LCA. These standards fall under the ISO 14000 series. The series contains two critical LCA standards:

1 **ISO 14040:** Principles and Framework provides the fundamental principles and guidelines for conducting LCA studies. It outlines the stages of assessment, data collection, and interpretation.

iii. Standards for Products and Materials Carbon Assessment

2 **ISO 14044:** Requirements and Guidelines complements ISO 14040 by specifying detailed requirements for performing LCA. It covers aspects such as goal definition, inventory analysis, impact assessment, and interpretation.

Adherence to *ISO 14040* and *14044* are generally required for an LCA to be considered robust, and to adhere to existing and emerging standards, regulations, and policies. Despite their significance, the bodies of *ISO 14040* and *ISO 14044* have remained largely unchanged since their initial release in 2006. Opportunities for revision arose in 2011, 2015, and 2021, and the next opportunity is scheduled for 2026. To address specific needs and developments, ISO introduced annexes to *ISO 14044:*

- **Annex C (2017)** recognizes *ISO 14067* (Carbon Footprint) and *ISO 14046* (Water Footprint) standards as compliant with *ISO 14044.* These annexes focus on single-impact assessments related to carbon and water, respectively.
- **Annex D (2021)** addresses allocation procedures concerning reuse, recycling, and multi-functional processes with co-products.

While intended to be part of *ISO 14044,* these annexes are separate and must be purchased and referenced individually. A summary of LCA-related ISO standards can be found in Table 3, and a full list of the ISO standards mentioned during the workshop is in Appendix A and C.

ISO environmental standards extend beyond LCA. For example, the Carbon Footprint and Water Footprint standards mentioned above fall under TC 207 on Environmental Management, SC 7 on Greenhouse Gases. SC 7 also developed several other standards on sustainable practices and environmental management.

3.1.2. MEMBER-SUPPORTED STANDARDS ORGANIZATIONS

In contrast to standards governed by WTO principles, many organizations exist wherein members collaboratively develop standards to address immediate and specific industry needs. The ensuing subsection outlines key examples of these member-supported standards organizations.

3.1.2.1. GREENHOUSE GAS (GHG) PROTOCOL

The GHG Protocol is a globally recognized initiative establishing standardized frameworks for quantifying, managing, and reporting GHG emissions across diverse sectors, encompassing both private and public entities. A collaboration spanning two decades between the World Resources Institute (WRI) and the World Business Council for Sustainable Development (WBCSD), the protocol engages with governmental bodies, industry associations, NGOs, and businesses.

Some of the key standards developed by the GHG Protocol include:
- Corporate Accounting and Reporting Standard (for private- and public-sector organizations).
- Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (for cities).
- Mitigation Goal Standard (for creating national and sub-national mitigation goals).
- Corporate Value Chain (Scope 3) Standard (for calculating Scope 3 emissions).

iii. Standards for Products and Materials Carbon Assessment

3.1.2.2. AMERICAN CENTER FOR LIFE CYCLE ASSESSMENT (ACLCA)

ACLCA is a nonprofit membership organization that provides education, awareness, advocacy, and communications to build capacity and knowledge of environmental LCA. ACLCA membership comprises members of industry, academia, government, consulting, and NGOs. ACLCA has developed guidance to help the LCA community adhere to ISO standards and to fill gaps in the current ISO standards. ACLCA guidance documents consist of the following guidance and tools:

- **ACLCA ISO 21930 Guidance (2013)** addresses concerns/questions around calculating inventory indicators and adds guidance on calculating non-Life Cycle Impact Assessment (LCIA) inventory metrics required for EPDs.
- **PCR Open Standard (2022)** supports the harmonization of PCR development across Program Operators for the delivery of standardized, consistent, and reliable PCRs and EPDs by providing technical frameworks that support industry wide protocols for developing high quality product category rules (PCRs).
- **PCR Open Standard – Process and Methods Toolkit (2022)** provides a two-part tool: 1) a process (checklist) and 2) methods & methodologies (addenda). The tool aims to create consistent and reliable PCR and EPDs for transparency, procurement, and supply chain environmental impact assessment data.
- **The PCR Open Standard Addenda** were developed to further harmonize PCRs and EPDs.
  - Guidance for Allocating Burdens and Benefits of Materials Shared Across Product Systems.
  - Guidance for Assessing Data Quality of Background Life Cycle Inventory Datasets.
  - Guidance for Quantifying Renewable Electricity Instruments in Environmental Product Declarations.

ACLCA also has several additional documents under development, including
- **Uncertainty** aims to provide guidance on how uncertainty is managed during the PCR development process and how to express uncertainty in EPDs.
- **Digital EPDs /openEPD** aims to address the need for an open data format for reporting and exchanging EPD information.
- **Data Specificity in EPDs** aims to provide a taxonomy for EPDs related to product, manufacturing, and supply chain specificities.

3.2. KEY STANDARDS RELATED TO DECARBONIZATION

ISO and the GHG Protocol, as previously discussed, serve as the basis for LCA and carbon accounting standards, respectively. Entities endeavoring to report their Scope 1-3 GHG emissions and measure progress towards decarbonization objectives predominantly rely on the GHG Protocol's frameworks. Meanwhile, ISO's LCA standards provide the fundamental principles guiding LCA practices. In tandem, ASTM manages several sector- and product-specific international standards, further enhancing the granularity and applicability of LCA methods. The following section provides more details regarding decarbonization standards.

3.2.1. LIFE-CYCLE ASSESSMENT STANDARDS

While *ISO 14040* and *ISO 14044* are the bedrock standards for LCA, including for defining different system boundaries, several other standards influence this landscape such as *ISO 21930 (Sustainability in buildings and civil engineering works — Core rules for*

iii. Standards for Products and Materials Carbon Assessment

environmental product declarations of construction products and services) (ISO, 2017), which provides additional details on system boundaries for LCAs. These boundaries are commonly referred to using the terms cradle (raw material extraction), gate (the manufacturer's gate), and grave (the end of life, e.g., landfill, incineration).

LCA usually starts with raw materials—or the "cradle"— and follows those materials as they are transported to a manufacturing facility where they are turned into a product. *ISO 21930* specifically relates to buildings and civil works projects, but Figure 6 adapts the system boundaries from the standard to be broadly applicable to most products. Section 5 of this report covers topics that extend beyond the boundaries defined by the concept of cradle-to-grave.

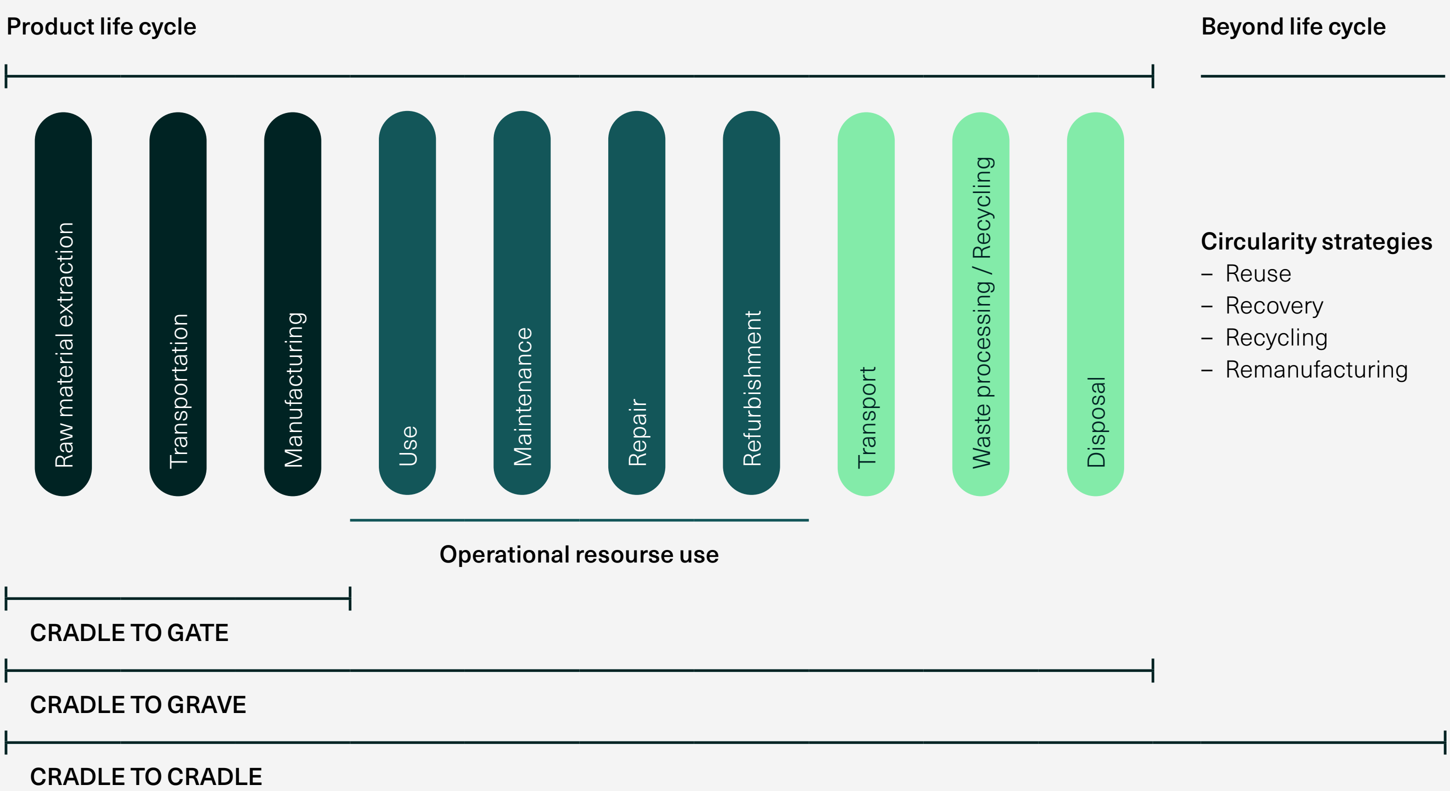


Figure 6 — A generalized system boundary for an LCA. Adapted from Masson (2023).

Data and methodology are critical to a robust LCA; ISO 14044 covers data and methodology, specifying ten attributes that must be addressed in an LCA:

1. Age of the data (time).
2. Geography covered.
3. Technology used.

iii. Standards for Products and Materials Carbon Assessment

4 Precision and variability of the data values (must be included in the critical review report).
5 Completeness of the data (measure the percentage of total data that is collected and reported).
6 How representative the data used is (i.e., how well do the data reflect the entity being modeled?).
7 Consistency: Qualitative assessment of whether the methodology is applied uniformly across the various components of the analysis.
8 Reproducibility: Qualitative assessment of whether the methodology and data values would allow an independent practitioner to reproduce the results reported in the study.
9 Sources of the data.
10 Uncertainty of the information (e.g., data, models, and assumptions).

ISO 14044 specifically identifies uncertainty as a necessary consideration for LCAs. All the above attributes have uncertainty associated with them. See ISO 14044 for additional details on these attributes.

3.2.2. CARBON ACCOUNTING

Life-cycle assessment is defined within ISO standards, offering a clear, consensus-based framework for assessment practices. In contrast, carbon accounting lacks a standardized definition within consensus-based standards, resulting in varying interpretations. The GHG Protocol defines carbon accounting for businesses as the process of identifying and calculating emissions associated with the business's operations for reporting and record keeping (World Resources Institute & World Business Council for Sustainable Development, 2004). Despite this widely adopted definition, the lack of an international standard leads to diverse interpretations of the term. Even during the workshop, the concept of carbon accounting was addressed by multiple speakers, each with differing perspectives. This discrepancy in how carbon accounting is understood and interpreted highlights a crucial gap in carbon accounting standards. Filling this gap is beneficial for two key reasons: first, it streamlines the measurement of the economic and ecological impact of products for use in decision making; and second, it amplifies the value proposition of sustainability-focused decisions, such as those underpinning green marketing initiatives. To navigate this issue, two distinct carbon accounting methods —the GHG Protocol and ISO 14064—and the concept of carbon allocation, all of which were discussed in the workshop, are explained below.

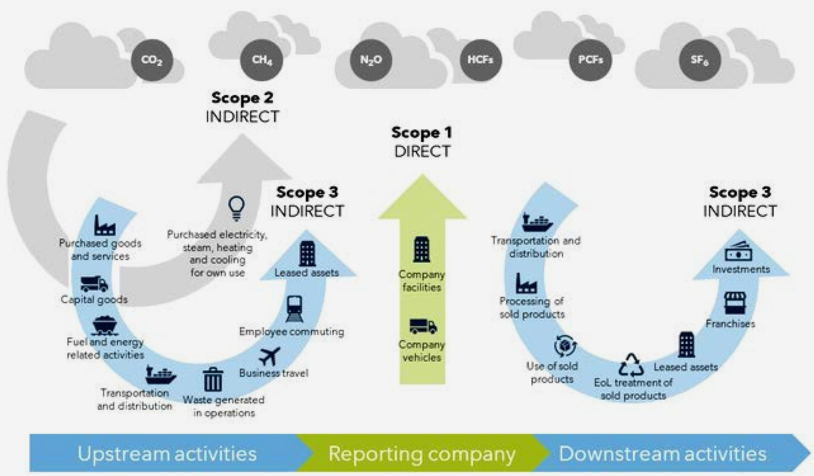
3.2.2.1. GHG PROTOCOL STANDARDS

The *GHG Protocol Corporate Accounting and Reporting Standard* (also referred to as the GHG Protocol Corporate Standard), initially published in 2001 and updated in 2004, covers accounting and reporting of the six GHGs covered by the Kyoto Protocol: carbon dioxide (CO2), methane (CH4), nitrous oxide (N2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF6). Since then, the GHG Protocol added guidance on accounting for indirect emissions (Scopes 2 and 3, see below). Another update to the Corporate standard is scheduled for 2025 (Huckins, 2023). In addition to the Corporate standard, the organization published other standards for measuring GHGs in cities, for projects and products, and associated with policy decisions (GHG Protocol, 2024). The Protocol divides emissions into the following three scopes (World Resources Institute & World Business Council for Sustainable Development, 2004), also depicted in Figure 7:

iii. Standards for Products and Materials Carbon Assessment

- **Scope 1** emissions are direct emissions from processes owned and operated by the organization (e.g., jet fuel emissions, natural gas emissions, propane emissions).
- **Scope 2** emissions are indirect emissions from purchased energy (e.g., electricity) in which the emissions are generated by a company other than the purchasing organization.
- **Scope 3** emissions are indirect emissions associated with the organization's entire value chain (upstream and downstream). The 15 categories of Scope 3 emissions are listed in Figure 7.

Figure 7 — An overview of the scopes of GHG emissions across the value chain, per the GHG Protocol's accounting and reporting standard (GHG Protocol, 2011).



Carbon accounting is similar to financial accounting and reporting in that carbon accounting principles, such as those found in the GHG Protocol, are intended to underpin and guide carbon accounting and reporting to ensure that the reported information truly reflects a company's carbon emissions. A challenge identified during the workshop was that unlike financial accounting, which consists of a general ledger that balances debit and credits, carbon accounting does not balance and can allow carbon to be double-counted. Specifically, carbon accounting includes accounting for Scope 3 emissions. One organization's Scope 3 emissions are another organization's Scopes 1 and 2 emissions. For example, emissions from electricity generated at a gas-fired power plant are Scope 1 emissions for the plant, but Scope 2 for the electricity's end user. Another accounting challenge regarding Scope 3 emissions discussed in the workshop is that it is difficult to collect and verify up-to-date emissions data on the potential variety of emissions up and down the supply chain. The GHG Protocol allows for the following four methods for calculating Scope 3:

- **Supplier Specific Method:** All data are specific to a supplier's product.
- The **Spend Based Method** applies the ratio of manufacturer total spend to supplier total revenue to suppliers total Scope 1 and 2 emissions to allocate emissions.
- The **Average Data Method** uses secondary data (i.e. industry average data).
- **Hybrid Method:** A combination of the above methods.

iii. Standards for Products and Materials Carbon Assessment

3.2.2.2. ISO 14064

ISO 14064 – Greenhouse gases is an international standard for measuring and reporting emissions at the organizational level. It is divided into three parts:

- **Part 1:** Specification with guidance at the organization level for quantification and reporting of GHG emissions and removals;
- **Part 2:** Specification with guidance at the project level for quantification, monitoring and reporting of GHG emission reductions or removal enhancements; and
- **Part 3:** Specification with guidance for the verification and validation of GHG statements.

Table 3 — Summary of ISO-related life cycle assessment (LCA) and greenhouse gas (GHG) standards, classified by technical committee (TC).

	ISO/TC 207			ISO/TC 146
	SC 3: Environmental labeling	**SC 5: Life cycle assessment**	**SC 7: Greenhouse gas and climate change management and related activities**	
2006	**ISO 14025** Principles and procedures	**IISO 14040** Principles and framework **ISO 14044** Requirements and guidelines		
2017		**ISO 14044 Annex C** Recognizes ISO 14046 & 14067		
2018			**ISO 14064-1** Quantifying and reporting GHGs (2018) **ISO 14067** Carbon footprint (2018)	
2019			**ISO 14064-2** Project-level emissions (2019) **ISO 14064-3** Verification/ validation requirements (2019)	
2021			**ISO 14065** Principles/ requirements for verifying bodies (2021)	**ISO 19694** GHG emissions in energy- intensive industries (Part 1 - General)
2022		**ISO 14044 Annex D** Allocation procedures		
2023			**ISO 14066** Competency for verifying bodies (2023)	**ISO 19694 Part 3** Cement **ISO 19694 Part 4** Aluminum **ISO 19694 Part 3** Ferroalloys and silicon
2024			**ISO 14068** Organizational claims (e.g., carbon neutral, climate negative, carbon-free)	

iii. Standards for Products and Materials Carbon Assessment

It has been pointed out that the *ISO 14064* standards complement the GHG Protocol. One document from the EPA suggests that the GHG Protocol sets minimum standards for measuring emissions and gives best practices for creating a GHG inventory, while ISO *14064 Part 1 (ISO 14064-1)* sets the minimum requirements for complying with these best practices (as Wintergreen & Delaney, n.d. explain, ISO identified what to do and the GHG Protocol explains how to do it). *ISO 14064-3* also adds a verification component that the GHG Protocol currently lacks (Persefoni, 2023).

3.2.2.3. CARBON ALLOCATION WITH ISO 14044

GWP that results from LCA studies is directly affected by the allocation method used in the LCA model. Carbon allocation is a means to assign inputs and outputs of a system to the resulting product(s). *ISO 14044* standardizes the method for allocating inputs and outputs, including carbon emissions, in an LCA (ISO, 2006b). The standard recommends allocation should be avoided by increasing the level of detail in the model or expanding the system, but this is often not feasible. Thus, LCA practitioners will allocate energy and other inputs based on production volumes or co-products based on economic value.

Consensus is needed to close the gaps in *ISO 14044* and standardize the allocation approach fit for different scenarios. Table 3 summarized the ISO standards coved in this section.

3.2.3. OTHER RELEVANT STANDARDS

Along with ISO/TC 207's 14000 series, the ISO/TC 146 on Air Quality was also discussed during the workshop—specifically its SC 1 on Stationary Source Emissions. The ISO 19694 series specifies how to quantify and report emissions in energy-intensive industries in general as well as requirements for specific industries, including recently released standards for cement, aluminum, lime, ferroalloys and silicon, and semiconductors and display industries (Table 4).

Table 4 — Other standards relevant to decarbonization and life cycle assessment.

GENERAL ASPECTS	**ISO 19694-1:2021** — published 2021
IRON AND STEEL	**ISO/AWI TS 19694-2** — under development (drafting stage)
CEMENT	**ISO 19694-3:2023** — published 2023
ALUMINUM	**ISO 19694-4:2023** — published 2023
LIME	**ISO 19694-5:2023** — published 2023
FERROALLOYS AND SILICON	**ISO 19694-6:2023** — published 2023
SEMICONDUCTOR AND DISPLAY INDUSTRIES	**ISO 19694-7: 2024** — published 2024
BUILDINGS	**ASHRAE/ICC 240P** — under review

iv. Data

One large gap identified during the workshop related to the collection and development of data used in LCA modeling. While the workshop focused on decarbonization, numerous participants and discussions emphasized the importance of having a full array of reliable LCA data throughout the modeling and interpretation processes. This section discusses the data needs identified in the workshop as well as progress to date on trying to address these needs, with particular focus on topics covered by workshop presentations and associated participant discussions.

4.1. DATA NEEDS FOR DECARBONIZATION

Workshop participants and presenters identified data needs for decarbonization. When polled, participants identified *comparability* to be the greatest LCA data-related issue they face, followed by *availability, accuracy, consistency, and harmonization* (Figure 8). Some also specified *end of life* and *location-specific data* as major issues. The workshop presentations listed similar data needs. For example, one speaker identified four key needs:

1 More, better, transparent data that are high quality and up to date, both for background and foreground data.
2 Harmonization throughout the LCA model (e.g., methods, data, assumptions).
3 Balancing the tradeoff between eliminating judgment choices (harmonizing modeling assumptions) and maintaining flexibility so practitioners can refer to their specific scenario (location- and facility-specific data).
4 Including “beyond the gate” (i.e., product use and post-use) impacts.
5 Similar data needs were highlighted throughout other workshop presentations and associated discussions.

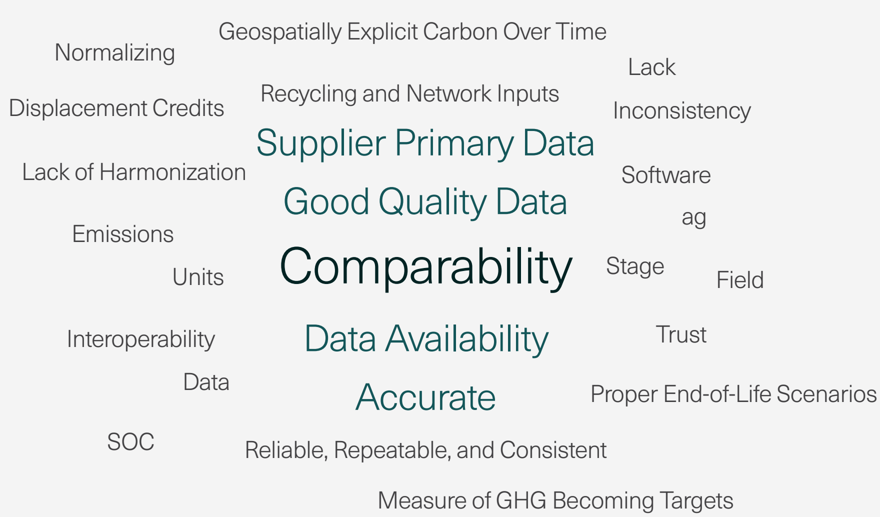


Figure 8 — Participant responses to the question “What is the greatest LCA data-related issue you face right now?” (N = 45)

These needs align with responses from both the U.S. EPA’s *Request for Information (RFI) to Support New Inflation Reduction Act Programs to Lower Embodied Greenhouse Gas Emissions Associated with Construction Materials and Products* (RFI EPA-HQ-

iv. Data

OPPT-2022-0924) (EPA, 2023), which was discussed at the workshop, as well as an internal poll of the members of the EPA Interagency Leadership Team on Background Data for EPD¬s (ILTBD). The EPA evaluated over 100 responses to their RFI and identified the most common keywords for background datasets for EPDs as the following: *public, available, updated, current, consistent, accessible, open,* and *free*. The ILTBD polled their members to identify characteristics describing ideal background datasets. The findings are grouped and defined in the following categories (Ingwersen, 2023):

- **Reviewed:** Data have been independently checked for quality assurance and reviewed by subject matter and LCA experts for accuracy and conformance to guidelines.
- **Relevant:** Data are relevant temporally, geographically, technologically, and market-wise, and were collected using adequate procedures.
- **Publicly available:** Data are accessible and free to access and use.
- **Transparent & reproducible:** The source of the original data inputs used to develop the background data profile are clearly documented to enable a third party to independently recreate the background data result based on the data documentation (metadata) with reported or linked data sources.
- **Based on representative public data & consistent data sources:** Data use federal or other public statistical data to the fullest extent possible, but allow verified industry data to fill knowledge gaps, and to the maximum extent possible, datasets as others should be based on the same underlying data.
- **Meet anticipated user requirements:** Data meet requirements for one or more known use cases.
- **Interoperable:** Data use data structure/nomenclature that enable utilization with external LCA datasets/software.
- **Maintained:** Plans and resources for future updates are present and communicated.
- **Used:** Data are already used in applications, indicating their value and relevance to end users.

These outcomes indicate clear general agreement across industry and government on the characteristics of public datasets needed to increase the number and quality of EPDs.

4.2.LCA DATA DEVELOPMENT AND MODEL STANDARDIZATION

Progress has been made to standardize methods for data collection, development, and curation throughout the product life cycle to support LCAs. These methods must allow for the collection of data that are comparable and reduces uncertainty. Standards can help resolve some of the needs identified in Section 4.1 through specifying and harmonizing

- LCI flow terminology (i.e., nomenclature),
- metadata requirements,
- data format and integration,
- quality,
- transparency,
- data collection,
- impact methods,
- interoperability,
- digitization, and
- automation.

iv. Data

Federal agencies and their partners are actively pursuing all of these factors. LCI data needs vary by application, with emissions factor data sources used for LCA ranging from measured data points to economy-wide models (e.g., environmentally extended input-output models) (Feraldi, 2023). Consistency is also required to allow for combinations of data at different levels of aggregation as well as from different locations around the world. Consideration must also be given to protecting proprietary data to increase the availability of foreground data. This section discusses public LCA resources and collaborative efforts targeting the needs discussed during the workshop.

4.2.1. FEDERAL LCA COMMONS

U.S. federal agencies have made significant strides toward improving standardization of LCA modeling, with much of this effort consolidated and coordinated through the Federal LCA Commons. This collaborative initiative brings together various federal agencies such as the EPA, U.S. Department of Agriculture (USDA), U.S. Forest Service (USFS), FHWA, Department of Defense, NIST, and several Department of Energy (DOE) national laboratories (National Energy Technology Laboratory (NETL), National Renewable Energy Laboratory (NREL), and Argonne National Laboratory (ANL) to share expertise and methods. The goal is to develop common federal data-modeling conventions and make federal datasets freely available through a web-based data repository, the Federal LCA Commons Data Portal (Federal LCA Commons, 2017).

The Data Portal serves as a comprehensive repository, housing datasets from multiple agencies (Federal LCA Commons, USFS, NREL, and EPA) and industry partners. It includes background LCI databases, harmonized data descriptions (i.e., ontology), data quality matrix, and usability guidance. All the contents are geared towards fostering free, trusted, transparent, and interoperable LCA data and modeling. For instance, the EPA's Federal Elementary Flow List (FEDEFL) streamlines LCI flow nomenclature, reducing redundancy and enhancing granularity. The Federal LCA Commons also provides FEDEFL-adapted impact methods (e.g., ReCiPe, Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts - TRACI 2.1, Cumulative Energy Demand, CED).

Furthermore, the Federal LCA Commons identifies key focus areas for future activities, categorized into standardization and verification tools for interoperability, gap analysis, and data-gap filling. Priorities include harmonizing file formats, developing technosphere flow mapping, standardizing LCI Data Collection Templates, and filling data gaps in areas such as alternative fuels and waste management.

Despite these efforts, awareness of the Federal Commons remains limited among stakeholders. Workshop participants expressed unfamiliarity or underutilization of the Federal LCA Commons resources, relying primarily on paid datasets for energy and transportation LCI data. It is crucial to raise awareness about the Federal LCA Commons and capitalize on its ongoing and future activities to enhance background data quality and transparency for LCA modeling across EPDs and software tools. One area of progress has been in more prescriptive background data source requirements or recommendations within PCRs, first for transportation data and more recently for electricity data.

4.2.2. PUBLIC BACKGROUND DATASETS

Federal agencies provide a variety of common background datasets, both directly and/

iv. Data

or through the Federal LCA Commons Data Portal. The Federal LCA Commons mega-repository includes common background datasets from federal agencies and partners in industry and academia, including LCA data at different levels of aggregation, both process-based and input-output-based LCA data, which are listed in Table 5 and described briefly below. All datasets in the Federal LCA Commons are compatible with the Federal Elementary Flow List (FEDEFL)-adapted impact methods provided in the Data Portal. The FEDEFL standardizes the structure and content of life cycle inventory data. Additional datasets are available directly from federal agencies or national laboratories, including Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) for transportation LCA data and Cambium for electricity GHG data, both of which will be discussed later in this section.

Table 5 — Federally available LCA data, impact methods, and other modeling resources and links to access the data.

NAME	ACRONYM	DESCRIPTION AND HOW TO ACCESS
FEDERAL LCA COMMONS		A mega-repository that holds datasets from multiple federal agencies (e.g., USFS/CORRIM, NREL, EPA) and industry partners Federal LCA Commons
ELECTRICITYLCI & ELECTRICITY BASELINE	**eLCI**	Collaboration between US EPA and NETL with contributions from ERG and NREL. GitHub (must use Python) Federal LCA Commons NETL (Excel format)
NREL US LIFE CYCLE INVENTORY	**USLCI**	Contains > 600 process LCIs across fuels combustion, utilities, transport, metals, minerals, agriculture, chemicals, resins, pulp & paper, plastics, composites, manufacturing, electronics, building products, and more NREL Federal LCA Commons
CAMBIUM DATASETS		Contain modeled hourly emission, cost, and operational data for a range of possible futures of the U.S. electricity sector through 2050, with metrics designed to be useful for forward-looking analysis and decision support. NREL
GREENHOUSE GASES, REGULATED EMISSIONS, AND ENERGY USE IN TRANSPORTATION	**GREET**	Tool that shows the environmental and energy life cycle impacts of vehicles and fuels. Argonne National Lab
FORESTRY AND FOREST PRODUCTS		LCA data on the production, use, and disposal of forest products from CORRIM and curated by the U.S. Forest Service. Federal LCA Commons

iv. Data

NAME	ACRONYM	DESCRIPTION AND HOW TO ACCESS
U.S. ENVIRONMENTALLY-EXTENDED INPUT-OUTPUT MODELS	**USEEIO models**	Gives an approach for estimating the environmental (e.g., carbon footprint) and economic (e.g., transactions across industry sectors) impacts related to the production or consumption of goods and services. EPA
CONSTRUCTION AND DEMOLITION (C&D) MANAGEMENT		Database describing the end-of-use (EoU) management of materials found in the built environment–e.g., asphalt pavement, asphalt shingles, gypsum drywall, wood, land-clearing debris. Federal LCA Commons
HEAVY EQUIPMENT		LCA data on heavy equipment from the EPA. Federal LCA Commons
MOTOR VEHICLE EMISSION SIMULATOR		An emission modeling system that estimates emissions for mobile sources at the national, county, and project levels for criteria air pollutants, GHGs, and air toxins EPA

The most widely known and used public database is NREL's USLCI, which was originally published in 2003 and is currently updated quarterly with over 600 process LCIs across fuels combustion, utilities, transport, metals, minerals, agriculture, chemicals, resins, pulp & paper, plastics, composites, manufacturing, electronics, building products, and more (Feraldi, 2023). A common misconception is that the data in the USLCI is all developed and updated by the federal government. In fact, the USLCI is a database populated by consulting, academia, and industry associations with some curation by NREL. USLCI is available through the Federal LCA Common Data Portal.

Energy is an input for every product in the economy, whether it is consumption up the supply chain, a direct input in the manufacturing process or facility operation, or fuel use during transportation or installation of the product. Federal agencies have developed LCI data for energy, including on-site consumption of fossil fuels and electricity, some of which is already available on the Federal LCA Commons Data Portal.

Electricity has the most available datasets, including both public and commercial datasets. Most LCA data users obtain energy LCI data through the datasets accessible in their preferred commercial software, which is consistent with the answers from workshop participants discussed previously. One of the most widely used public sources for electricity data remains the USLCI (i.e., Electric Power Generation, Transmission and Distribution), which is primarily data for North America and is outdated (2008 or 2010). To address the use of "old" data for the U.S. electric grid, several federal agencies/ national laboratories collaborated to produce the Federal LCA Commons first official data product: the Electricity Baseline. The Electricity Baseline takes data collected from over 7000 generating facilities and develops estimates for average emissions rates at different aggregation levels (balancing authority, FERC regions and subregions, and national average) including imports and exports.

iv. Data

The Electricity Baseline provides both generation-based emissions rates (consistent with the approach used for the Emissions & Generation Resource Integrated Database—e-GRID) and consumption-based estimates, the latter of which better represents actual emissions associated with a unit of on-site electricity consumption. The Electricity Baseline is available through (1) the LCA Commons Data Portal and can be exported in both JavaScript Object Notation for Linked Data (JSON-LD) and International Life Cycle Data System (ILCD) formats, (2) NETL in excel format, or (3) GitHub using python. The residual grid mix is also provided, which adjusts for generation exclusively claimed by retail consumers (e.g., renewable purchase programs). The Grid Mix Explorer Excel tool provided by NETL allows for evaluating hypothetical grid mixes to determine the impact on GHG and other emissions. NETL collaborated with NIST in 2023 to leverage the Electricity Baseline to develop future projections of electricity emissions using two EIA scenarios (Reference Case and Low Zero-Carbon Technology Cost Case). The resulting LCA data provides consumption-based annual average emissions rates by balancing authority through 2050 for both scenarios (Kneifel et al., 2022). In 2024, NETL and NIST plan to update these estimates, expand scenarios to include two based on NREL's Cambium modeling, and leverage the generating unit data from Cambium's long-run marginal emission rate projections to develop LCA results.

LCA data for on-site consumption of fossil fuels has also been developed. NETL has developed energy baselines for natural gas and petroleum. For example, NETL's natural gas life cycle model (available publicly in Excel) provides a detailed look into sources of emissions. Major data sources are the EPA GHG Reporting Program (GHGRP), measurement-informed studies, engineering calculations, and GHG Inventory (GHGI).

The same collaboration between NETL and NIST for electricity also provided future projections of LCA results for on-site fossil fuel consumption using EIA projections for fuel type specific regions (i.e., production basin for natural gas and the Petroleum Administration for Defense District (PADD) for fuel oil and propane). The estimated variation in emissions is more significant across regions than it is over time because efficiency and technological change are assumed to be minimal in both EIA scenarios (Kneifel et al., 2022).

As with energy, transportation LCI data are most commonly obtained from commercial datasets in users' software tool of preference. However, federal agencies provide transportation LCA data both through the Federal LCA Commons and ANL's GREET Model and associated tools. The LCA Commons Data Portal includes data on heavy equipment and transportation in the EPA's MOtor Vehicle Emission Simulator (MOVES). MOVES is "a state-of-the-science emission modeling system that estimates emissions for mobile sources at the national, county, and project level for criteria air pollutants, greenhouse gases, and air toxics." (US EPA, 2016).

GREET provides a consistent, standard system boundary and LCA methodology for complete LCA and avoidance of leakage or shifting of emissions, including total energy consumption (non-renewable and renewable), fossil fuel energy use, greenhouse gas emissions, air pollutant emissions, and water consumption. The tool also provides a process-based, rigorous LCA of both powertrain technologies and fuel systems for road, marine, rail, and air transportation. Underlying data are regularly updated for specific

iv. Data

transportation modes in real-world applications, and they include more than 100 fuel production pathways and more than 70 vehicle/fuel systems. GREET includes holistic modeling across economic sectors to incorporate emission impacts of technology improvement over time.

GREET compiles data from a range of sources. Background data are collected for baseline technologies and systems from the EIA (Annual Energy Outlook projections), EPA (electricity), and USGS (water), some of which is linked through USLCI data. Some foreground data are collected from field/facility operation data of oil sands and shale oil operations, ethanol plant energy use, and farming data (USDA). Other foreground data use model simulations, including Aspen Plus for fuel production, ANL Autonomie for fuel economy, EPA MOVES for vehicle emissions, EPA CAMPD for stationary emissions, LP models for petroleum refinery operations, and electric utility dispatch models for marginal electricity analysis. Additionally, other data are collected through collaborations with other national laboratories, universities, and industry (i.e., fuel producers and technology developers and automakers and system components producers).

Although GREET is a powerful tool for transportation LCA analysis, some limitations and areas for improvement remain that could be targeted to improve the model. Gaps include limited coverage of non-road transportation (e.g., specialty transportation technologies and modes, heavy-duty mining equipment) and a lack of consequential impacts of large-scale production of low-carbon fuels (e.g., biofuels and e-fuels). The GREET model could also be improved in several areas: additional impact categories, regional fidelity (e.g., electrification technologies), payload impacts on fuel economy for various powertrain technologies and transportation modes, incorporation of embodied carbon for infrastructure and vehicle cycle modeling, and indirect effects (e.g., pavement maintenance). Note that the GREET data are in their own repository and are not currently compatible with the Federal LCA Commons Data Portal.

The Federal LCA Commons also includes data on forestry as well as economic sector-level LCA data. The regionalized forestry and forestry products data were provided by a collaboration between the Consortium for Research on Renewable Industrial Materials (CORRIM) and USFS. The data covers a range of life cycle stages, such as logging, milling, and manufacturing of wood building materials. The data are linked to USLCI background data and are compatible with FEDEFL-adapted impact methods provided in the Data Portal. The Federal LCA Commons includes the U.S. Environmentally-Extended Input-Output (USEEIO) model, which is a combination of economic and environmental models. The USEEIO model uses data on inputs to and outputs from industries, their final consumption, and value added provided in the form of input-output tables from the Bureau of Economic Analysis. These tables are paired with environmental data from various public sources to develop LCA impact category metrics based on impact per dollar spent (US EPA, 2020). The USEEIO provides environmental information for economic transactions between 411 US industry sectors. Due to the source of data and time required to create input-output models, the data are always dated. For example, the current USEEIO (v2.0.1-411) is primarily based on 2012 data.

4.2.3.INTERNATIONAL DATA

iv. Data

The focus of this section until now has been on U.S. LCA data, but economic activity is global in nature. For a specific product, each of its life cycle stages may occur in a variety of regions around the world. For accurate LCA analysis, trustworthy, interoperable data for all regions of the world are needed. Currently, significant data for Europe and North America exist, but information from other regions is limited.

Figure 9 — Summary of international LCA data and sector contributions to global GHG emissions assessments. Cell shading under "Description" corresponds to the contribution of that column to total GHG emissions based on subjective data. Cell shading under "Europe and North America" and "Other Regions" corresponds to subjective data availability. Darker boxes indicate higher contributions. Adapted from Suh (2023).

		Europe & North America			Other Regions		
Sector	**Description**	**P-LCA**	**IO-LCA**	**EPDs**	**P-LCA**	**IO-LCA**	**EPDs**
11	Agriculture, Forestry, Fishing and Hunting						
21	Mining, Quarrying, and Oil and Gas Extraction						
22	Utilities						
23	Construction						
31-33	Manufacturing						
42	Wholesale Trade						
44-45	Retail Trade						
48-49	Transportation and Warehousing						
51	Information						
52	Finance and Insurance						
53	Real Estate and Rental and Leasing						
54	Professional, Scientific, and Technical Services						
55	Management of Companies and Enterprises						
56	"Administrative and Support and Waste Managemenet and Remediation Services"						
61	Educational Services						
62	Health Care and Social Assistance						
71	Arts, Entertainment, and Recreation						
72	Accommodation and Food Services						
81	Other Services						
92	Public Administration						
48-49	Transportation and Warehousing						

iv. Data

Additionally, the interoperability of the existing data is lacking. Figure 9 provides a summary of both the availability of LCA data by sector and region as well as the relative contribution of a given sector in each region to global GHG emissions. Technological and geographical coverages remain uneven. The highest emitting activities of industrialized countries are relatively well-covered by process-based LCI (P-LCA) databases, such as energy, materials, agriculture, manufacturing, and transportation. However, industrializing economies, downstream manufacturing, and services largely rely on environmentally-extended input-output LCA (IO-LCA) datasets (i.e., average emissions per dollar spent in a sector).

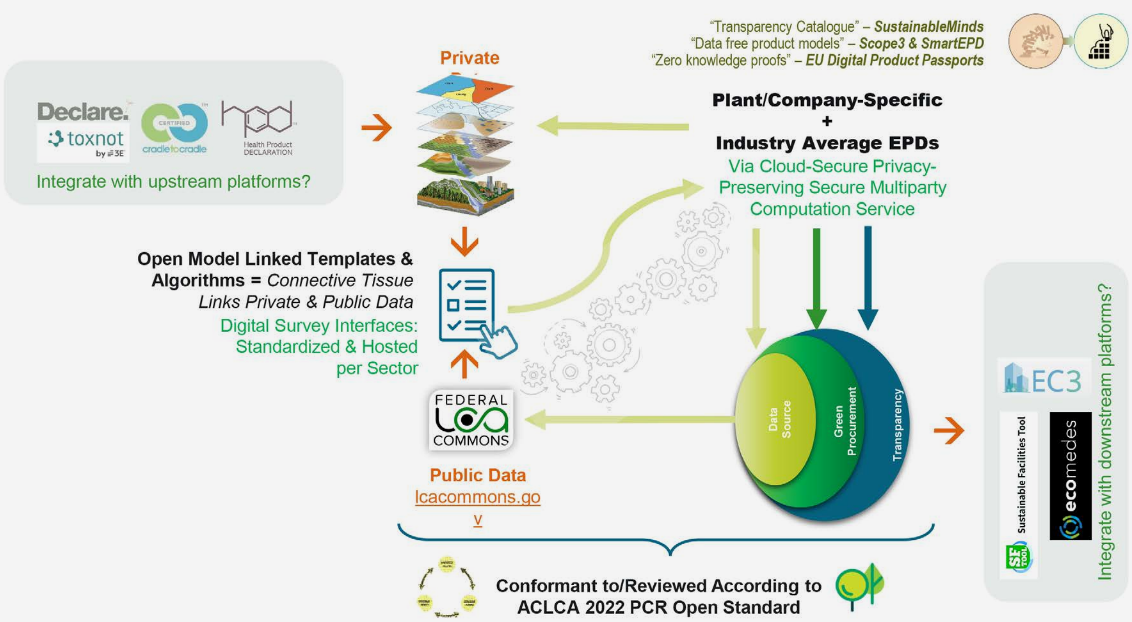
4.2.4. DIGITIZED OPEN LCA MODELS

Although increasing and improving publicly available datasets will assist in standardizing LCA modeling for product comparability, site-specific, private (i.e., primary) data are still needed to improve accuracy of the estimates and help distinguish good practices. Thus, accurate, standardized LCA modeling requires consideration of the trade-offs between maximizing data transparency and protecting this private data. For LCA results to be comparable, the methodologies and data selected for inputs to the LCA model must be consistent across all products. Background data that are not specific to a given product should be the same across all LCA results being compared while foreground data that are unique should be collected and used in the LCA model. Greater granularity of the foreground data will improve the accuracy of an LCA study, but making such data public could a) reduce or eliminate a real or perceived competitive advantage for the producer and/or b) reveal information about trade secrets and other intellectual property. To increase industry's willingness to participate, protecting such data in a manner that still provides transparency as to the source of the LCA data is vital.

An idea that has received a lot of attention and support is the use of digitized open model-linked templates to protect proprietary data while providing trusted results. This concept would develop an LCA model template for all products in a product category to use with specified data types and sources (e.g., public background datasets, industry wide averages) to use for all inputs. The appropriate data would then be replaced by protected foreground data for the specific product for the study. Only the protected data would not be made publicly available. This approach is shown in Figure 10 and has been defined in the ACLCA PCR Open Standard (2022) (ACLCA, 2022), as highlighted in Section 3.1.2.2. These digitized open models could be used with public industry level data to generate both industry-wide averages for use as benchmarks and product specific model results to be reviewed and compared to the benchmarks, all while protecting private data.

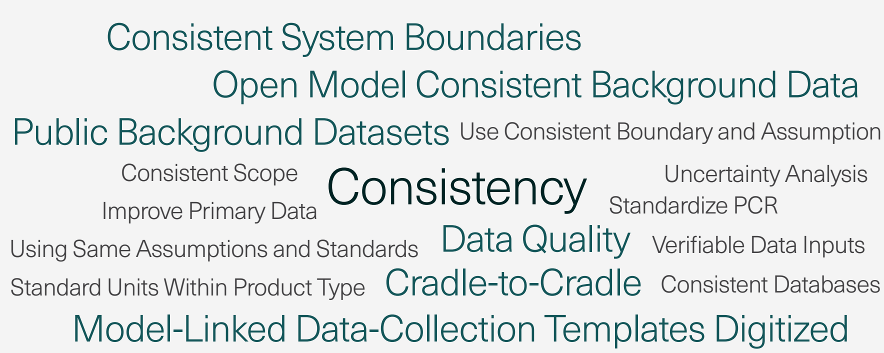
iv. Data

Figure 10 — Example of a digital open model-linked template approach (Feraldi, 2023).



As shown in the responses in Figure 11, workshop participants identified such a standardized digital open model using consistent assumptions, boundary conditions, and high quality, verifiable primary and background datasets as key to improving product comparability.

Figure 11 — Workshop audience's responses to the question "In five words how can LCAs be improved to better compare products?" (N = 34)



v. Beyond the Gate

Thus far, this report has focused on cradle-to-gate analysis and excluded discussion of the use and end of use (EoU) product life-cycle stages. These latter stages are classified as “beyond the gate” and include everything that occurs after the manufacture of the material or system. This includes shipping; installation or erection; initial service, maintenance and repair or replacement; potential reuse and recycling, or end of life. These stages come after the sale of a product, leaving the producer with less control over the outcomes. There is wide variability in both use-stage applications and the severity of the service environment, which then influences the EoU options for recovery. These life-cycle stages are often critical to accurately measuring the economic and environmental performance of products and systems.

While significant work has been done to account for cradle-to-gate life-cycle stages in LCA and EPDs, major gaps exist in the rules and standards for including beyond the gate considerations. While generalized models can be created, every application and service environment is potentially different in terms of service life and maintenance expectations, making standardized data for these stages inherently difficult to collect. While standards and models exist for assessing specific aspects of the life cycle performance and environmental impacts of EoU stages (e.g., Minimum criteria for comparing whole life building assessment (LCA) for use with codes, standards and rating systems [e.g., ASTM Practice E2921]) and comparative performance data are available for some service environments, no international standards provide detailed guidance on what is required for comprehensive use-stage assessment. Without consistent use-stage assessment procedures, cradle-to-cradle (material is reused or recycled into new products at the end of life) or cradle-to-grave (material is not recycled or reused) LCAs and EPDs are not comparable. Measuring the impacts of product performance, maintenance, and replacement beyond the gate is becoming increasingly relevant, creating the need to collect and apply projected climate data for the built environment (see Section 5.1.1 for an example). This is also relevant as countries and industries adopt circular economy practices, changing the considerations for how to allocate environmental impacts (see Section 5.2.1 for an example).

Presentations at the workshop provided an overview of existing resources and research while identifying the gaps that exist beyond the gate by exploring the data and standards needs for comprehensive cradle-to-cradle or cradle-to-grave LCAs. This includes the variables that should be considered when developing meaningful product- and application-specific assessments, as well as the opportunities for technological improvements to more effectively use and recapture resources. The speakers indicated that disregarding beyond the gate stages in purchasing decisions could lead to suboptimal environmental and economic decisions; workshop participants specifically identified application performance requirements and data collection as the biggest challenges in assessing material or system performance across the use stage of the life cycle. Participants also ranked the categories of standards related to beyond the gate stages that should be addressed to fill these standards gaps (Table 6). This section discusses four opportunity areas for beyond the gate presented in the workshop: resilience and material deterioration in the use stage and impact allocation and recycling in the EoU stage.

v. Beyond the Gate

Table 6 — Participants' responses to the question "Which types of standards are most needed for filling the "Beyond the Gate" standards gap? Choose up to two."
(N = 26)

STANDARDS NEED	PERCENTAGE OF TOTAL VOTES
Reuse	54%
Recycling	50%
Material performance	46%
Resilience risk analysis	27%
Material separation	19%
Other	15%

5.1. USE STAGE

The criteria for selecting sustainable and resilient materials and systems are evolving rapidly, but assessments of material or system performance during the use stage are often not done, are based on service environment generalizations, or are limited to material degradation. Assessments of performance in specific applications in buildings or infrastructure frequently rely on broad, sometimes flawed, assumptions. Coastal zone size, exposure to deicing salts and pollutants, and various other environmental and design elements can profoundly affect use-stage performance. These variables and other factors such as increasing incidences of weather extremes and sea level rise are dynamic, making it more difficult to accurately assess and predict failures, and deterioration mechanisms—e.g., corrosion—for the product or service's lifespan.

Many published resources exist on specific service environments to aid in assessment of material and system performance. They can be combined with design requirements, service life, and maintenance and replacement expectations to create use-stage LCA. This level of assessment is frequently done in severe industrial environments and transportation systems because of the economic incentive to avoid expensive shutdowns and life safety concerns. In other use sectors, there is often lack of knowledge of the factors that should be on the assessment "check list" and there are often no requirements to conduct such assessments.

5.1.1.RESILIENCE

ASTM Guide E3341 for General Principles of, the first international standard on the topic, defines resilience as the ability to prepare for anticipated hazards, adapt to changing conditions, to withstand and limit negative impacts due to events, and to return to intended functions/services within a specified time after a disruptive event (ASTM International, 2024). Trends in extreme weather events, terrorism, sea level rise, flooding, and their associated impacts are significantly increasing. As a result, the needs for resilience in materials and products for these changing circumstances are both increasing and changing in nature, and new areas are being affected. Current design practices need to adapt to the evolving environmental circumstances. As stated earlier, incorporating this type of data into LCA is often overlooked. While assessing these new risks can seem challenging, there are predictive models—such as those developed by the insurance industry for terrorism- and weather-related losses, LightningCast AI's model for forecasting

v. Beyond the Gate

wildfire incidents, the U.S. National Oceanic and Atmospheric Administration's (NOAA's) predictions for sea level rise—that can be used during design and in both project-specific and generalized models.

Extreme weather events

Although only representative of insured events, global data from the insurance industry portrays a consistent rise in both natural and human-induced incidents and associated insured losses. According to the Swiss Re Group, global insured catastrophe losses were $112 billion USD in 2021, the fourth highest since 1970, and the 10-year average suggested that the annual 5-6% increase in insured losses seen over the past few decades is persisting (Swiss Re Group, 2021).

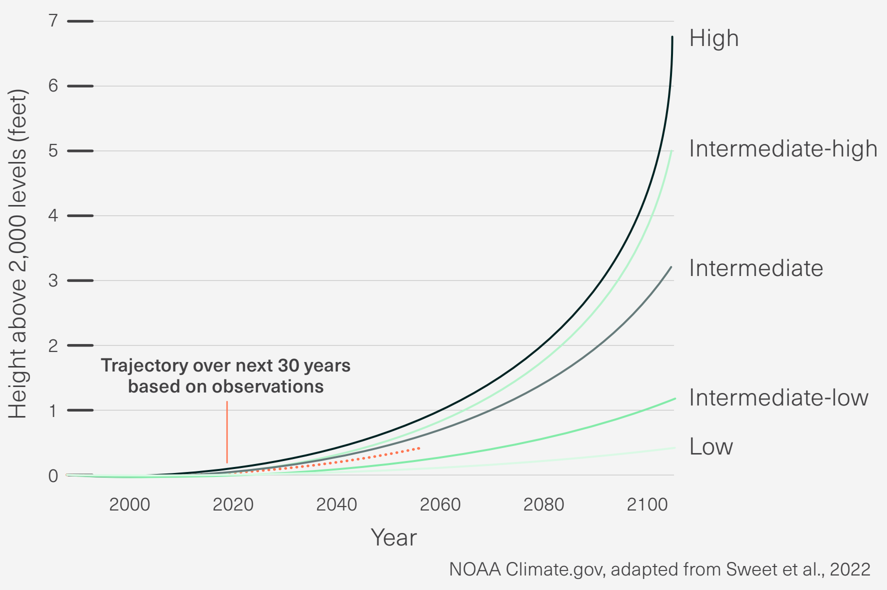
Terrorism

Terrorism incidents have risen in the U.S., from 20 in 2012 to 103 in 2020 (START, 2022), leading to a need to consider improving the resilience of buildings, industry, and infrastructure against human-caused attacks.

Sea level rise

According to NOAA, sea levels around the globe have been rising since they started recording in 1880, with an acceleration seen from 1993 to 2022. A global average increase of 8 in. to 9 in. (21 cm to 24 cm) has been seen since 1880, with 4 in. (101.2 mm) of that recorded since 1993. Predictions of potential rates of sea level rise over the rest of this century vary widely but are generally expected to increase, as shown in Figure 11 (Lindsey, 2022).

Figure 12 — Observed sea level rise 2000-2008, with projections to 2100 for six future pathways (low to high). The pathways differ based on future rates of greenhouse gas emissions and global warming and differences in plausible rates of glacier and ice sheet loss (Lindsey, 2022).



v. Beyond the Gate

Designers can develop more accurate use-stage LCAs to adapt to these trends by combining use-stage application and service-environment-focused LCA assessments, which are already commonly used in industry and transportation with a resilience risk assessment. It is common during the design stage to assess site-specific corrosion performance and design resilience separately when making material and system selection decisions (Houska, 2023). This can result in a system that is considered resilient when it is initially installed but fails when an event occurs due to material or system deterioration. This failure to consider deterioration in the service environment can make timely recovery impossible, cause avoidale damage, and shorten the life of the system and perhaps other systems that it was designed to protect. In turn, this shortens the amortization period of the initial investment, invalidating initial projections of life-cycle impacts including maintenance and replacement rate assumptions that are typically based on industry averages. The environmental impact calculated for the entire life of the product may remain the same, but that product's expected lifespan is cut short. Thus, the product's environmental impact increases over the design life of the system. This is also the case for unplanned replacements or repairs—e.g., repairing buildings or infrastructure due to unpredicted extreme events. The environmental impacts associated with these unplanned, unexpected, or earlier-than-planned repairs and replacements increase the overall environmental impacts over the system design life (see Section 5.1.2).

For these reasons, workshop speakers and participants in this section emphasized that LCAs must consider material and systems sustainability, resilience, and durability for a given product application in a specific service environment. It must also do this in a way that is comparable, meaning that a) the use-stage performance of materials should be comparable so practitioners can decide which product to select and b) LCAs and EPDs should be comparable so consumers and practitioners can make decisions that are fit for purpose. Therefore, use-stage LCA should, at a minimum, consider:

1. Expected service life.
2. Current service environment assessment.
3. Predictable service environment changes.
4. Resilience risk assessment.
5. Expected performance of system component materials.
6. Expected maintenance and replacement frequency and the environmental impact of those maintenances and replacements.

Several existing resilience standards exist, although none connect resilience and LCA. ASTM E3341 addresses resilience in natural and anthropogenic systems and covers foundations for four resilience principles: "planning and preparation, adaptation, withstanding and limiting impacts, and recovery of operations and function" (ASTM International, 2024). Governments around the world are also considering community resilience when assessing homeland security risks. ASTM Guide E3350 for Community Resilience Planning for Buildings and Infrastructure was developed by the committee on Homeland Security (E54) and gives an analytical framework on community resilience (ASTM International, 2022). ASTM Guide E3130 for Developing Cost-effective Community Resilience Strategies(from the committee on Performance of Buildings (E06) (ASTM International, 2021a) is also intended to help with community planning; this standard

v. Beyond the Gate

focuses on economic decision guidance evaluating investment strategies designed to improve community resilience through strengthening the ability to respond, withstand, and recover from disruptive events.

The Federal Highway Administration (FHWA) is also considering community level resilience in their resilience assessments for transportation. During the workshop, speakers from the FHWA suggested a need to integrate and standardize social impacts and metrics for resilience into LCA. One standardization gap they identified is the need to develop a consensus between the bottom-up and top-down frameworks. Bottom-up resilience assessment focuses on a single product or project and is useful for identifying specific areas of improvement within a given system boundary, such as reducing a building's risk of wildfire damage. Top-down assessment focuses on a specific economic activity, such as reducing the risk of a national electrical grid failure. Examples of these approaches can be found in publications by the National Academies of Sciences, Engineering, and Medicine (outlined in their reports titled (*Building and Measuring Community Resilience,* 2019) and (*Investing in Transportation Resilience,* 2021), respectively).

5.1.2. MATERIAL DETERIORATION

An LCA study often relies on average service life and recycling data, making general assumptions about material and system performance. Designers use these assumptions to make decisions when designing for the built environment. However, these assumptions can 1) be based on inaccurate data or data that are not relevant to the application or service environment in question and 2) change as the environment changes. To overcome these problems with assumptions, we need methods that incorporate better data or models and changes to the environment into design decisions.

What might meet service life requirements in one service condition scenario could fail quickly in others. High maintenance and frequent replacements due to improper specification significantly escalate the embodied GHG emissions (and other environmental impacts) and operating costs of materials and systems, imposing substantial environmental and economic burdens. Separate from increased maintenance and replacement, the deterioration of an inappropriate material into the environment reduces recycling or reuse potential and releases that material into the environment. Moreover, considerable human health and safety risks are associated with failures, necessitating their consideration in sustainable, resilient design (Houska, 2023). Workshop speakers highlighted why standards for use-stage LCA are needed to ensure sufficient and consistent information is used for LCA to make better projections and avoid unanticipated costs and environmental impacts.

These LCA gaps were illustrated using the example of corrosion. Corrosion is caused by naturally occurring phenomena or application-specific exposures (e.g., industrial exposure) that deteriorate a substance (e.g., metal) or its properties as the result of its exposure to a service environment. In 2002, a joint National Association of Corrosion Engineers (NACE) / FHWA report found the direct annual cost of metallic corrosion in the U.S. to be US$276 billion, or 3.1% of the U.S. gross domestic product (GDP) for that year (G. H. Koch et al., 2002). Prior studies documented that this economic and environmental cost was ongoing:

v. Beyond the Gate

- **1950 H.H.Uhlig** — US study 2.1% of GDP.
- **1970 T.P.Hoar** — UK study 3.5% of GDP.
- **1974 Japan study** — 1.2% of GDP.
- **1974 Battelle/NBS** — U.S. study 4.5% of GDP.

A more recent NACE-led international project estimated the global cost of corrosion to be US$2.5 trillion, equivalent to 3.4% of the global GDP (G. Koch et al., 2016). While these studies were metal-specific, premature failure of materials (e.g., all types) and the systems that rely on them for function is a widespread and much larger problem. While corrosion causes immense economic and physical material losses, especially when products and systems use inappropriate specifications, it also has significant environmental implications. Deterioration can limit or eliminate recycling or reuse. Failed materials often enter the environment and can significantly harm the ecosystem and human health, as can the substances used for maintenance or repair of failing systems.

Compounding this issue is the dynamic nature of the natural- and human-driven trends discussed previously, rendering older research on material deterioration unreliable as a predictor of future performance. Consequently, elevated maintenance requirements and premature replacements significantly inflate realized ownership costs, associated GHG emissions, and other environmental and social impacts.

Material deterioration frequently intersects with the changes in weather and climate patterns discussed in Section 5.1.1. One example given in the workshop explained that much larger sections of the land are classified as “coastal” than most decision-makers realize (Houska, 2007). The traditional assumption made by corrosion experts was that only locations within five to ten miles of the coast have coastal chloride exposure and that there is minimal chloride salt deposition beyond the first mile inland. However, data gathered around the world have documented that this is not the case, and coastal zones can extend 50 or more miles inland, affecting 60% of the world’s population.

As sea levels rise, coastal groundwater is lifted closer to the surface while also becoming saltier and more corrosive. This results in an increased danger of corrosion and failure of critical systems—such as sewer lines, roadways, and building foundations—due to interaction with this shallower and saltier groundwater (U.H. News, 2024). This is not only occurring at greater distances from the coastline but also in regions far from the coast that were once part of the seabed, such as parts of the southwestern U.S. Figure 13 provides the total annual chloride deposition for the contiguous U.S., which shows significant chloride deposits inland on all coastal states, the influence of salt lakes and areas formerly under the ocean, and reinforces the need to approach design differently.

Another popular misconception is that deicing salts only affect material on or immediately beside roadways. In fact, research done by the National Atmospheric Deposition Program, Illinois Department of Transportation, and Battelle National Laboratory documented salts

v. Beyond the Gate

traveling up to 1.2 miles downwind of highways and salt mists around downtown areas of cities. As the use of more corrosive deicing products has increased (e.g., calcium and magnesium chloride), corrosion consultants are finding that they are carried even further from roadways than prior deicers (Houska, 2007).

These popular misconceptions about the size of the coastal zone and the areas affected by deicing salts in combination with changing use and weather patterns have led to avoidable failures. Changing trends in sea levels and temperatures may exacerbate this situation. Achieving a shift from popular misconceptions to data-based decision making is critical for reducing material waste and the negative economic and environmental impacts associated with waste.

The primary barriers to reducing the unnecessary environmental and economic costs associated with inappropriate material selection are a lack of:
- knowledge about the service environment factors that cause material deterioration,
- available data, and
- requirements for such an assessment.

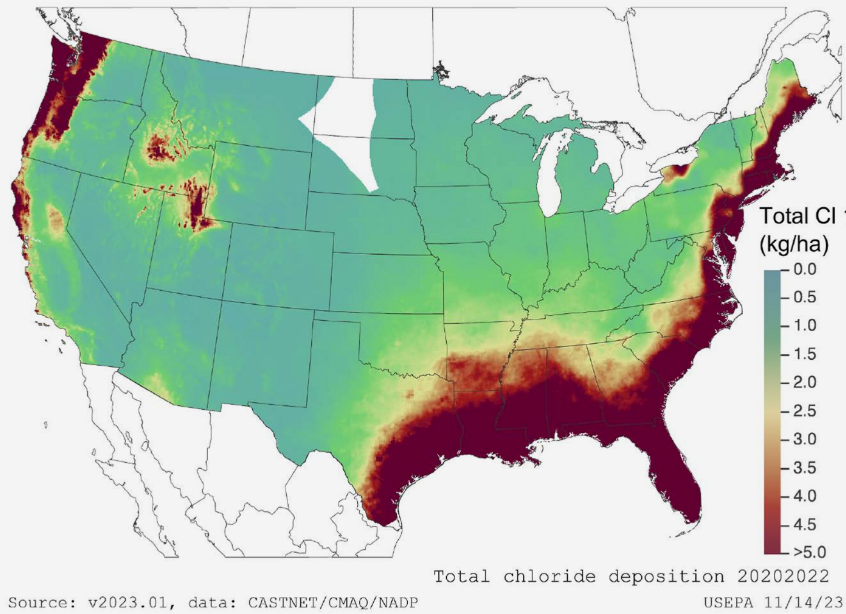
This is further complicated by misunderstandings. While buildings and structures must be assessed to meet other service environmental-specific factors like wind loading, seismic, and fire code requirements, corrosion assessment is not required and often poorly understood.

Multiple speakers expressed views that use-stage LCA should at minimum include a standardized checklist of the factors that affect material deterioration along with easily accessible resources so that a decision maker who is not a corrosion expert can perform a basic assessment of the factors that can cause material deterioration. Separate from individual project assessment, this allows the development of comparative LCA models that are appropriate for standardized typical environments. Both current and predictable service environment changes should be considered as well as the impact of short-term events, such as flooding.

It is common for multiple significant but predictable events to occur at the same time or in sequence, making a similar checklist necessary, considering resilient design requirements. For example, fires have occurred in cities and plants during flooding events caused by major storms. In addition, a major storm after a wildfire increases flooding risks. Combining predictable resilient risk assessment with a standard exposure assessment within the use-stage LCA will make far more accurate cradle-to-cradle and cradle-to-grave LCA possible as it will recognize the unique nature of applications and service environments and will promote better decision-making. ASTM already has product-specific resilient design specifications, and more are in development.

v. Beyond the Gate

Figure 13 — U.S. NADP coastal zone areas with 5 kg/ha or more of total chloride deposition for 2021 (NADP, 2023).



5.2. END OF USE (EOU)

End of use (EoU) is part of the product life cycle, but it is often not included in LCAs. This is in part because, while standards and tools exist for measuring life cycle impacts from cradle to gate, there is little guidance on how to consider reuse and EoU strategies in LCA. According to the speakers, this lack of standards can lead to two problems. First, practitioners can manipulate the outcomes of LCA, on purpose or by accident, which in turn may lead to greenwashing (i.e., manipulation of the outcome of LCA studies by choosing favorable assumptions). As discussed in the workshop, this manipulation can manifest in several ways (Mistry, 2023):

- Claiming higher than accurate recycling efficiencies, underestimating the product's impact;
- Assuming a product or material has multiple lives, underestimating the environmental impacts of each life;
- Ignoring disposal or landfilling impacts; and
- Claiming a material or product is recycled or more readily or completely recycled than is realistic.

The second problem with integrating reuse and EoU into LCA is that organizations have their own internal methods for evaluating the impacts of reuse and EoU, making it difficult to accurately compare LCAs (and EPDs) across different organizations. Thus, when developing standards to overcome the barriers above, a voluntary, consensus process is necessary. This section suggests ways that the environmental impacts of materials at their EoU should be allocated to avoid these two challenges and goes into details on considerations that LCA practitioners and standards developers should make when allocating the impact of recycling.

v. Beyond the Gate

5.2.1. ALLOCATING ENVIRONMENTAL IMPACT

All materials and products have environmental impacts across their life cycles, from resource extraction to end of use (EoU). It is important that LCA studies account for and properly allocate these impacts, as accurate metrics and allocation encourage the adoption of recovery strategies (e.g., recycling and remanufacturing) and reduce opportunities for greenwashing (B. Reck, 2023). However, accurately measuring and allocating these EoU strategies has been challenging. Several considerations for integrating EoU into LCA studies were identified (Mistry, 2023):

- **Reuse:** A product's environmental impacts may be distributed across multiple life cycles, thus reducing the impact for each product lifespan.
- **Material recovery:** Recovery strategies, like recycling and remanufacturing, reduce impacts of materials extraction (e.g., mining, harvesting).
- **Energy recovery:** The energy recovered can offset the need for other fuels, thus potentially reducing environmental impacts of a product or system using that energy.
- **Landfilling:** Environmental impacts of storing materials in landfills should be measured and included in estimated impacts.

Certain EoU options are preferable to others. The recently released ISO 59004 Circular economy — Vocabulary, principles and guidance for implementation outlines and defines the different EoU options for recirculating resources back into the economy–called "value retention" processes (ISO, 2024):

1 Refuse
2 Rethink
3 Source
4 Reduce
5 Repair
6 Reuse
7 Refurbish
8 Remanufacture
9 Repurpose
10 Cascade
11 Recycle
12 Recover energy
13 Re-mine

Although the standard does not include instructions for integrating these value recovery methods into LCA, it states that, in general, lower number methods (e.g., repair) should be prioritized over higher number ones (e.g., remanufacture). However, organizations should still consider which method works best for meeting their goals while taking an entire product life cycle perspective. This strategy generally follows the waste hierarchy for resource management (Mistry, 2023).

Workshop presenters and participants did highlight one standard that gives allocation guidance –ASTM Guide E3199 for Alternative Allocation Approaches to Modeling Input

v. Beyond the Gate

and Output Flows of Secondary Materials and Related Recycling Scenarios in Life Cycle Assessment. ISO 14044 only offers one approach for handling recycling materials (e.g., recycled content), which is problematic because of the differences between materials and their sometimes application- or composition-driven differences in recycling potential. ASTM Guide E3199 includes all of the widely accepted approaches for modeling recycling. The annexes contain guidance on how to allocate EoU scenarios for copper, flue gas desulfurization (FGD) gypsum, glass, plastics, post-consumer gypsum, stainless steel, and supplementary cementitious materials based on the unique recycling approaches used for each material; this way, LCA practitioners have a standardized approach agreed on by not only the industry but also the peer review that is part of the international standard setting process. One speaker suggested that more materials and industries should be included in this annex—specifically paper and other wood products, other metals, and concrete (Mistry, 2023).

Multiple factors must be considered when creating new standards or annexes on how to allocate 1) different material types and 2) value-retention processes. One factor is that material-specific annexes identifying the appropriate modeling approach for LCA recycling scenarios must consider the data availability for that material. Many materials do not have scaled and up-to-date material flow data. The materials in the ASTM Guide E3199 annexes contain accurate, third-party verified data based on national and global recycling rates and provide references that research and the resultant energy savings or costs from reuse and EoU pathways. However, this level of detail is not currently available for many materials, and leading practitioners to have to estimate or use historical data. In addition, while new value recovery technologies are emerging (e.g., chemical recycling, reuse), few have reliable LCI data. All of this means that, for materials not included in ASTM Guide E3199, research will be needed by practitioners to determine if sufficient reliable data exist and they and LCA tools must factor in uncertainty when it does not. The next subsection explores what standards developers should consider when allocating the environmental impact of different materials in an LCA study for one value-retention process: recycling.

5.2.2. RECYCLING

Two primary approaches to including recycling in LCA were presented at the workshop (Mistry, 2023):

1. In the **recycled content** approach, the benefits of recycling are allocated to the product design stage, thus incentivizing practitioners to use recycled content in their products. This approach is prioritized when incentives are needed to use recycled content due to, for example, recycled content being lower quality or higher price than its virgin equivalent.
2. !n the **end of life** approach, the benefits of recycling are allocated to the stakeholder that is recycling the material. This approach prioritizes higher recycling efficiencies and avoiding material losses to landfills.

A third “hybrid” option uses some combination of both approaches. *ISO 14044* suggests the recycled content approach; however, workshop participants suggested that this may not be the best approach for all scenarios, as the best approach may depend on whether it makes more sense to prioritize recycling or the use of recycled content.

v. Beyond the Gate

Both approaches require that practitioners understand the different types of recycling and relevant metrics. One speaker distinguished between functional and non-functional recycling (B. Reck, 2023). Functional recycling reduces the demand for virgin materials and avoids landfills and their associated emissions. Non-functional recycling (i.e., downcycling) creates secondary material of lower quality and value than its previous manifestation; it is an open-loop process and therefore does not replace the need for virgin material (Graedel et al., 2011; United Nations Environment Programme, 2011). The former strategy is more favorable because it avoids the impacts associated with virgin material extraction. The EoU recycling rate describes how much material is returned as secondary feedstock through functionally recycled only, whereas the non-functional EoU recycling rate measures the rate of downcycled material (United Nations Environment Programme, 2011).
This distinction is important when factoring recycling into LCA studies.

Another necessary consideration when integrating recycling into LCA studies is material type. Different materials have different rates of recycling, reuse, and material recovery, and LCA should account for these different rates when allocating environmental impact. According to the Recycling Materials Association,[3] in principle using recycled materials can theoretically decrease energy consumption from 27% for office paper to as much as 90% for aluminum ingot (Recycled Materials Association, 2024). However, these energy savings must also account for several factors. First, the purity of the recycled material coming into the recycling system. Second, whether it is undergoing functional or non-functional recycling. Third, the energy intensity of the recycling process and whether this intensity is included in the energy savings estimate. In addition, scrap recycling is common for metals, but LCA studies must distinguish between the *old scrap ratio* (post-consumer) and the *new scrap ratio* (generated during manufacturing). The old scrap ratio is the fraction of recycled content that comes from old scrap (Graedel et al., 2011; B. K. Reck & Graedel, 2012); not distinguishing between these types of scrap could perversely incentivize manufacturers to make their manufacturing process less efficient, thus generating excess new scrap that can be counted as recycled feedstock (B. Reck, 2023).

3 Formerly the Institute of Scrap Recycling Industries (ISRI).

vi. Summary of the Gaps

As the workshop concluded, gaps and needs for consensus-based standards became clear, as did the need to address the entire life cycle of products and materials and not just partial impacts (e.g., cradle-to-gate). Addressing the entire product life cycle (e.g., cradle-to-cradle) provides guidance for improved decision making across the life cycle of products and systems. When asked to identify in three words or less what LCA-related challenges could be solved by new standards, workshop participants cited broad topics including reference scenarios, consistency, comparability, transparency, uncertainty, machine readability, and EoU modeling as well as specific topics such as biogenic carbon (carbon sequestered in biological materials) and concrete carbonation (absorption of carbon dioxide by concrete after installation).

In addition to broad LCA-related challenges, workshop participants and speakers suggested and ranked standards gaps and needs based on the workshop (Table 7). Several basic needs were identified in the poll, including quality assessment for LCAs; improving data used in LCAs; and ways to make LCAs and their data easier to identify, use, and compare. The highest priority areas for standards were data quality, LCA model templates, biogenic carbon, and LCA quality (45-50% of participants). Also considered important were input data collection, selection, and comparison (34-39% of participants).

Standards for biogenic products (e.g., wood, paper, bio-based plastic) was identified as a high priority standards gap; while the workshop speakers did not discuss biogenic carbon specifically, many of the gaps in data, carbon footprints, and EoU identified also apply and should be considered when developing standards specifically for biogenic carbon. Foundational standards are needed to increase consistency in accounting for and allocating biogenic carbon sequestration and emissions in LCA and carbon accounting. Standards must also clarify the quantification of biogenic carbon and the timing of its sequestration and release into the atmosphere to validate carbon emissions estimates. These estimations are vital to the sale and purchase of reduced, sequestered, or avoided emissions (through compliance and voluntary carbon markets, which are often based on projects that sequester biogenic carbon (e.g., reforestation) (e.g., Mercer & Burke, 2023)). Thus, biogenic carbon is integral to the topic of the workshop and this report (i.e., decarbonization). The EPA's 2024 Reducing Embodied Greenhouse Gas Emissions for Construction Materials and Products grant program awarded funding to several organizations to measure and standardize biogenic carbon across several built environment material types, including wood, bamboo, and hemp (US EPA, 2023).

Table 7 — participants identified standards gaps during the workshop, then prioritized them at the end of the event (N = 38).

STANDARDS NEED	PERCENTAGE OF TOTAL VOTES
Classification of data quality for LCA	50%
LCA model templates (including digital formatting)	50%
Measuring, calculating, and applying biogenic carbon to LCAs (biogenic carbon accounting)	47%
Evaluating the quality of LCAs	45%

vi. Summary of the Gaps

Selecting and comparing LCA input data	39%
Collection of LCA input data	34%
Reference scenarios for LCA end-of-life (circularity) modeling	32%
Minimum criteria for assessing application-specific LCAs for materials and systems	24%
Minimum criteria for designing to facilitate material recycling	24%
Selecting and modeling energy data in LCAs	24%
Selecting and modeling transportation data in LCAs	16%
Minimum criteria for assessing resilience risk factors for use in LCAs for materials and systems during the use stage	8%

These results align with several existing efforts. One is the EPA's near-term priorities of developing a carbon labeling program for government procurement. The EPA also has grant programs aiming to increase the number and improve the quality of EPDs, which require both specific standards focused on EPDs as well as foundational standards on which additional standards can be built. For example, standardizing the process for selecting background data for an LCA will provide the basis for more consistent EPD results. In some cases, current guidance and resources—like those provided by the Federal LCA Commons (and associated agencies) and ACLCA—can be leveraged to accelerate the creation of these standards through the voluntary consensus standards process. In other cases, creating standards will require a more intensive development process, particularly to incorporate the EoU stages. For example, an EPA grant was awarded to ACLCA and several other organizations to create and update PCR standards (US EPA, 2023).

Table 8 summarizes the standards identified as needed by integrating the presentations and discussions with the polls. The table highlights where those needs are most relevant. Two new work items (precursors to a standard) have already been proposed based on the workshop:

1. Minimum criteria for comparing materials and systems during built environment use stage life cycle assessments (LCA) (WK90102)
2. Standard practice for preparing an environmental and human exposure screening report (ESR) for substances used in the built environment (WK90146)

Additional work items are expected to be proposed in the near future to begin to address standards gaps identified in the workshop and this report.

vi. Summary of the Gaps

Table 8 — Summary of standards ideas for ASTM International to develop. Standards are marked with an X for workshop session topics that apply to the standard and if that workshop session mentioned the standard.

Standard	WORKSHOP SESSION LCA Standards	 Better Data	 Carbon Footprints, Baselines and Reporting	 Beyond the Gate
MODELING, ANALYSIS, AND REPORTING				
Standard LCA model templates.		●		
Standardized LCA modeling nomenclature and documentation requirements (including format of data sources and other inputs, supply chain details).		●		
Standard guide for modeling and reporting on biogenic carbon.	●	●	●	●
Standards on inclusion of uncertainty in LCA modeling across life cycle stages.		●		●
Standard projection scenarios to use as the basis or modeling material performance for a given location (e.g., service life).				●
Standard guidance for multi-criteria analysis (sustainability/resilience/durability/circularity).				●
ALLOCATING IMPACT				
Standard(s) for allocation approaches in light of increasing circular economy practices for material recovery.				●
Methods for assessing environmental impact for EoU scenarios.				●
Methods to predict EoU recovery scenarios and integrate them into LCA.				●

vi. Summary of the Gaps

Standard	WORKSHOP SESSION LCA Standards	Better Data	Carbon Footprints, Baselines and Reporting	Beyond the Gate
TERMINOLOGY, BACKGROUND DATA, AND REFERENCES				
Standard definitions for terminology (e.g., “carbon accounting”).	●		●	
Standard practice for developing reference scenarios (e.g., end of use modeling).	●	●	●	●
Standards for data collection and development (including transparency).		●		
Standards for background data quality assessment and selection.		●	●	
CONSENSUS STANDARDS FROM EXISTING EFFORTS *				
Convert existing non-consensus standards and guidelines into consensus standards (e.g., ACLCA guidance).	●	●	●	●
Convert LCA resources in the Federal LCA Commons into standards (e.g., FEDEFL).		●		
Standards to improve PCR and EPD quality and quantity. Such standards can support the EPA’s carbon labeling program and grant programs.	●	●	●	●

* Existing efforts identified here are broad and may include standards needs identified in other categories in this table.

Conclusion

Assessing the life-cycle impact for a given product is challenging at best. LCA is becoming an increasingly popular tool for measuring the environmental impact of a product or service and ways to reduce that impact. However, while well-established and useful for broadly comparing products, LCA has limitations. One is that it approximates product impacts. Assessments are made based on available and similar datasets, introducing a degree of uncertainty that, if not controlled for, is not generally reliable for product-to-product comparisons. Understanding the intricacies of how different LCAs are conducted, the tools and datasets used, and details about how the given products were produced are all necessary to realistically estimate product impact. For example, workshop speakers showed that LCAs conducted with different regional data can have broadly differing outcomes.

While a portfolio of existing standards for LCA exists (see Appendix B and C), more standards are needed to make LCA results more comparable and reproducible, and therefore useful for decarbonization efforts. The workshop covered three categories of these needs:

1. Consistency in existing methods and tools;
2. Better data; and
3. New methods for addressing the full product life cycle, with emphasis on what happens “beyond the gate.”

Workshop participants also identified standards needs not specifically covered in the workshop, such as measuring biogenic carbon and integrating it into LCA.
The workshop identified current efforts to fill some of these gaps, such as:

- The EPA’s work supporting more standards in this area, particularly with respect to PCR and EPD development (e.g., the 2024 Reducing Embodied Greenhouse Gas Emissions for Construction Materials and Products grant program (US EPA, 2023)), and
- Efforts across federal agencies that are targeting the expansion and improvement of underlying datasets used in LCA.

The “beyond the gate” topic is the least developed or accounted for within LCA standards and datasets. Several factors result in a high-level of uncertainty surrounding the impacts of a product once it enters its use phase:

- Whether the product is operated in manner consistent with its design,
- How it is maintained,
- The service environment in which it operates, and
- End-of-use outcomes for the product.

These factors are compounded by the ever-evolving and ever-changing conditions under which the product performs, such as changing climate trends, EoU recovery options, and successful recovery. Yet these factors can also significantly influence environmental performance, including both releases into the environment as well as the degree of material losses and the impact for recovery.

Conclusion

A concerted effort is needed across industry and governments to improve LCA standards to support more uniform and informed studies that ensure accuracy and transparency, and thus improve trust in the results and better inform decision making towards reaching decarbonization goals. Voluntary consensus standards, including those made by ASTM International, are vital to this process. Standards development efforts are already underway, including ASTM new work items discussed at the end of Section 6, as well as discussions between ASTM International and the larger LCA community (e.g., ACLCA) to leverage currently published guidance on a range of LCA-related topics to develop new industry consensus standards.

References

ASTM STANDARDS

ASTM E3130 *Guide for Developing Cost-Effective Community Resilience Strategies,* ASTM E3130-21 (Voluntary), West Conshohocken, PA: ASTM International,) https://www.astm.org/e3130-21.html (Published), approved Aug. 1, 2021.

ASTM E3350, *Guide for Community Resilience Planning for Buildings and Infrastructure,* ASTM E3350-22 (Voluntary), West Conshohocken, PA: ASTM International, https://www.astm.org/e3350-22.html (Published), approved Sept. 15, 2022.

ASTM E3341 *Guide for General Principles of Resilience,* ASTM E3341-23a (Voluntary), West Conshohocken, PA: ASTM International, https://www.astm.org/e3341-23a.html (Published), approved Dec. 15, 2023.

ISO STANDARDS

ISO 14025:2006, *Environmental labels and declarations—Type III environmental declarations—Principles and procedures,* International Organization for Standardization (ISO), (2006a), https://www.iso.org/obp/ui/#iso:std:iso:14025:ed-1:v1:en (Published)

ISO 14044:2006, *Environmental management—Life cycle assessment—Requirements and guidelines,* International Organization for Standardization (ISO), (2006b), https://www.iso.org/standard/38498.html (Published).

ISO 21930, *Sustainability in buildings and civil engineering works; Core rules for environmental product declarations of construction products and services,* International Organization for Standardization (ISO), (2017), https://www.iso.org/standard/61694.html (Published)

ISO 14040:2006, *Environmental management—Life cycle assessment—Principles and framework*, International Organization for Standardization (ISO), (2022), https://www.iso.org/standard/37456.html (Published)

ISO 59004, *Circular economy—Vocabulary, principles and guidance for implementation*, International Organization for Standardization (ISO), (2024), (Published)

REFERENCED WORKS

ACLCA, *2022 ACLCA PCR Guidance – Process and Methods Toolkit* (1.0), 2022, https://aclca.org/wp-content/uploads/2022-ACLCA-PCR-Guidance_v1_Introduction_05252022.pdf

ACLCA, *The Power of Life Cycle Assessment: Data Driven Decision Making for Environmental Sustainability,* 2023, American Center for Life Cycle Assessment (ACLCA).

Building and Measuring Community Resilience: Actions for Communities and the Gulf Research Program (with Committee on Measuring Community Resilience, Office of Special Projects, Policy and Global Affairs, & National Academies of Sciences, Engineering, and Medicine), National Academies Press, 2019, https://doi.org/10.17226/25383

Climate Corporate Data Accountability Act, SB 253, California State Legislature, 2023, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240SB253

References

Climate Leadership Council, *Counting Carbon: Voluntary and Mandatory Emissions Reporting Programs* (p. 32) [Nonprofit], Climate Leadership Council, 2023, https://clcouncil.org/report/counting-carbon/

Council of the European Union, Council gives final green light to corporate sustainability reporting directive [Government], *Press Releases,* 2022, November 28, https://www.consilium.europa.eu/en/press/press-releases/2022/11/28/council-gives-final-green-light-to-corporate-sustainability-reporting-directive/

Council on Environmental Quality, *Net-Zero Emissions Procurement by 2050* [Government], Office of the Federal Chief Sustainability Officer, 2022, https://www.sustainability.gov/federalsustainabilityplan/procurement.html

Deloitte, Climate-related Financial Disclosures [Consultant], *Deloitte United Kingdom,* 2022, https://www2.deloitte.com/uk/en/pages/audit/articles/climate-related-financial-disclosures.html

Directorate-General for Financial Stability, Financial Services and Capital Markets Union, The Commission adopts the European Sustainability Reporting Standards—European Commission, *Finance: European Commission,* 2023, July 31, https://finance.ec.europa.eu/news/commission-adopts-european-sustainability-reporting-standards-2023-07-31_en

Ellen MacArthur Foundation, *An innovation pathway to decarbonization: Circular economy solutions for policymakers and industry in the US* [NGO], Ellen MacArthur Foundation (EMF). 2024, https://www.ellenmacarthurfoundation.org/industrial-decarbonization

EPA, *RFI and Webinar Announcement for Sustainable Marketplace/Environmentally Preferable Purchasing Program* [Government], Regulations.Gov., 2023, https://www.regulations.gov/docket/EPA-HQ-OPPT-2022-0924/comments

Executive Order on Catalyzing Clean Energy Industries and Jobs Through Federal Sustainability, 14057 Executive Order, 2021, https://www.whitehouse.gov/briefing-room/presidential-actions/2021/12/08/executive-order-on-catalyzing-clean-energy-industries-and-jobs-through-federal-sustainability/

Federal LCA Commons,*Welcome to the Federal LCA Commons | Life Cycle Assessment Commons* [Government], Federal LCA Commons, 2017, https://www.lcacommons.gov/

Feraldi, R., *Current and Future Activities to Improve Background LCA Data,* Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry, Virtual, 2023, October 10, https://astm.webex.com/recordingservice/sites/astm/recording/d63ac45149ab103c9dea1abdfe4a29b5/playback

FHWA, *FHWA Climate Challenge* (p. 2), U.S. Department of Transportation, 2022a, https://www.fhwa.dot.gov/infrastructure/climatechallenge/factsheet.pdf

References

FHWA, *FHWA Climate Challenge—Quantifying Emissions of Sustainable Pavements* [Government], Federal Highway Administration (FHWA), 2022b, October 19, https://www.fhwa.dot.gov/infrastructure/climatechallenge/projects/index.cfm

GFANZ, Amount of finance committed to achieving 1.5°C now at scale needed to deliver the transition [Glasgow Financial Alliance for Net Zero (GFANZ)], *Glasgow Financial Alliance for Net Zero,* 2021, November 3, https://www.gfanzero.com/press/amount-of-finance-committed-to-achieving-1-5c-now-at-scale-needed-to-deliver-the-transition/

GHG Protocol, *Corporate Value Chain (Scope 3) Accounting and Reporting Standard* (p. 152) [Nonprofit], World Resources Institute, 2011, https://ghgprotocol.org/sites/default/files/standards/Corporate-Value-Chain-Accounting-Reporing-Standard_041613_2.pdf

GHG Protocol, *Standards | GHG Protocol* [Nonprofit], Greenhouse Gas Protocol, 2024, https://ghgprotocol.org/standards

Graedel, T. E., Allwood, J., Birat, J.-P., Buchert, M., Hagelüken, C., Reck, B. K., Sibley, S. F., & Sonnemann, G., What Do We Know About Metal Recycling Rates? *Journal of Industrial Ecology,* 2011, Vol 15, No. 3, pp. 355–366, https://doi.org/10.1111/j.1530-9290.2011.00342.x

Hapuwatte, B. M., Mathur, N., & Morris, K. C., Emissions Avoidance Quantification and Allocation Framework for Secondary Materials Marketplaces Supporting the Circular Economy, *Volume 1: Additive Manufacturing; Advanced Materials Manufacturing; Biomanufacturing; Life Cycle Engineering,* V001T04A004, 2023, https://doi.org/10.1115/MSEC2023-104125

Houska, C., *Deicing Salt – Recognizing the Corrosion Threat* (p. 11), TMR Consulting, 2007, https://www.imoa.info/download_files/stainless-steel/DeicingSalt.pdf

Houska, C., *Beyond the Gate: Performance Through End of Life,* Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry, Virtual, 2023, October 11, https://astm.webex.com/recordingservice/sites/astm/recording/fb6faa884a74103cbbff223b3c02d1f2/playback

Huckins, S., Standards Update Process: Frequently Asked Questions | GHG Protocol [Nonprofit], *Greenhouse Gas Protocol,* 2023, June 1, https://ghgprotocol.org/blog/standards-update-process-frequently-asked-questions

Ingwersen, W., *A Background Data Plan to Support Environmental Product Declarations used in Public Procurement,* ACLCA 2024 Conference, Burlington, VT, 2023, September 27. https://aclcaconference.org/

Investing in Transportation Resilience: A Framework for Informed Choices (with Committee on Transportation Resilience Metrics, Policy Studies, Transportation Research Board, & National Academies of Sciences, Engineering, and Medicine), Transportation Research Board, 2021, https://doi.org/10.17226/26292

References

IPCC, *Global Warming of 1.5 oC: Summary for Policymakers* (Special Report), The Intergovernmental Panel on Climate Change (IPCC), 2018, https://www.ipcc.ch/sr15/

IPCC, *Climate Change 2022 – Impacts, Adaptation and Vulnerability: Working Group II Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* (1st ed.), Cambridge University Press, 2023, https://doi.org/10.1017/9781009325844

Kneifel, J. D., Gagnon, P., & Jamieson, M., Times (and the Grid) are A-Changin': Publicly Available, Forward-Looking Electricity Databases for GHG and LCA Projections, *National Institute of Standards and Technology* (NIST), 2022, https://www.nist.gov/publications/times-and-grid-are-changin-publicly-available-forward-looking-electricity-databases-ghg

Koch, G. H., Brongers, M. P. H., Thompson, N. G., Virmani, Y. P., Payer, J. H., CC Technologies, Inc., & NACE International, *Corrosion Cost and Preventive Strategies in the United States [Final report]* (FHWA-RD-01-156, R315-01), U.S. Federal Highway Administration (FHWA), 2002, https://rosap.ntl.bts.gov/view/dot/40697

Koch, G., Varney, J., Thompson, N., Moghissi, O., Gould, M., & Payer, J., *International Measures of Prevention, Application, and Economics of Corrosion Technologies Study* (p. 216). National Association of Corrosion Engineers (NACE), 2016, http://impact.nace.org/documents/Nace-International-Report.pdf

Lindsey, R., *Climate Change: Global Sea Level* [Government], Climate.Gov., 2022, April 29, http://www.climate.gov/news-features/understanding-climate/climate-change-global-sea-level

Macri, D., *Enhancing Transparency, Standardization and Reporting Criteria for EPDs,* Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry, Virtual, 2023, October 10,
https://astm.webex.com/recordingservice/sites/astm/recording/d63ac45149ab103c9dea1abdfe4a29b5/playback

Masson, S., *Life Cycle Stages,* One Click LCA Help Centre, 2023, August 16, https://oneclicklca.zendesk.com/hc/en-us/articles/360015064999-Life-Cycle-Stages

Michaelowa, A., Shishlov, I., & Brescia, D., Evolution of international carbon markets: Lessons for the Paris Agreement, *Wiley Interdisciplinary Reviews: Climate Change,* Vol 10, No. 6, 2019, Article 6, https://doi.org/10.1002/wcc.613

Mistry, M., *The Importance of Standards: LCA and Recycling,* Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry, Virtual, 2023, October 11, https://astm.webex.com/recordingservice/sites/astm/recording/fb6faa884a74103cbbff223b3c02d1f2/playback

References

NADP, *Total Deposition Science Committee (TDep)* [Non-Profit], National Atmospheric Deposition Program (NADP), 2023, https://nadp.slh.wisc.edu/committees/tdep/#tdep-maps

Office of the Federal Chief Sustainability Officer, *Federal Buy Clean Initiative* [Government], US Office of the Federal Chief Sustainability Officer, 2023, https://www.sustainability.gov/buyclean/

OSFI, *Climate Risk Management* [Government], Office of the Superintendent of Financial Institutions (OSFI) Canada, 2023, July 7, https://www.osfi-bsif.gc.ca/en/guidance/guidance-library/climate-risk-management

Persefoni, *Carbon Accounting Standards—Persefoni* [Company], Persefoni, 2023, https://www.persefoni.com/learn/carbon-accounting-standards

Reck, B., *Reducing the Embodied Carbon of Materials through Reuse and Recycling: Metals and Plastics,* Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry, Virtual, 2023, October 11, https://astm.webex.com/recordingservice/sites/astm/recording/playback/fb6faa884a74103cbbff223b3c02d1f2

Reck, B. K., & Graedel, T. E., Challenges in Metal Recycling, *Science,* Vol 337, No. 6095, 2012, pp. 690–695, https://doi.org/10.1126/science.1217501

Recycled Materials Association, *Sustainability* [Non-Profit], Recycled Materials Association, 2024, https://www.isri.org/sustainability

Segal, M., Brazil to Require Mandatory Sustainability Reporting from 2026, *ESG Today,* 2023, October 25, https://www.esgtoday.com/brazil-to-require-mandatory-sustainability-reporting-from-2026/

START, *Global Terrorism Database 1970—2020* [Dataset], National Consortium for the Study of Terrorism and Responses to Terrorism (START), 2022, https://www.start.umd.edu/gtd/

Suh, S., *Global Data Compatibility and Consistency,* Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry, Virtual, 2023, October 10, https://astm.webex.com/recordingservice/sites/astm/recording/d63ac45149ab103c9dea1abdfe4a29b5/playback

Swiss Re Group, *Global insured catastrophe losses rise to USD 112 billion in 2021, the fourth highest on record, Swiss Re Institute estimates* | Swiss Re, Swiss Re, 2021, December 14, https://www.swissre.com/media/press-release/nr-20211214-sigma-full-year-2021-preliminary-natcat-loss-estimates.html

The White House, *Federal-State Buy Clean Partnership Principles* (p. 5) [Government], The White House, 2023.

References

U.H. News, Rising seas to eat away at underground infrastructure in Hawaii, globally | University of Hawaii System News [University of Hawai'i News (UH News)], *UH News - Research,* 2024, April 15, https://www.hawaii.edu/news/2024/04/15/underground-infrastructure-corroding/

United Nations Environment Programme, I. R. P., *Recycling Rates of Metals: A Status Report,* 2011, https://wedocs.unep.org/20.500.11822/8702

US EPA, *Summaries of the FY 23–24 IRA 60112 Grant Selections: Reducing Embodied Greenhouse Gas Emissions for Construction Materials and Products* [Government], U.S. Environmental Protection Agency (US EPA), 2023, September 19, https://www.epa.gov/greenerproducts/grant-program-reducing-embodied-greenhouse-gas-emissions-construction-materials-and

US EPA, O, *Latest Version of Motor Vehicle Emission Simulator (MOVES),* U.S. Environmental Protection Agency (US EPA), 2016, May 10, https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves

US EPA, O, *US Environmentally-Extended Input-Output (USEEIO) Technical Content* [Data and Tools], U.S. Environmental Protection Agency (US EPA), 2020, May 5, https://www.epa.gov/land-research/us-environmentally-extended-input-output-useeio-technical-content

U.S. Securities and Exchange Commission, Press Release: SEC Adopts Rules to Enhance and Standardize Climate-Related Disclosures for Investors [Government], *Press Releases,* 2024, https://www.sec.gov/news/press-release/2024-31

WBCSD, & WRI, *The Greenhouse Gas Protocol, A Corporate Accounting and Reporting Standard,* World Business Council for Sustainable Development (WBCSD); World Resources Institute (WRI), 2004.

Wintergreen, J., & Delaney, T., ISO 14064 International Standard for GHG Emissions Inventories and Verification [Government], *U.S. EPA,* (n.d.), Retrieved February 19, 2024, from https://www3.epa.gov/ttnchie1/conference/ei16/session13/wintergreen.pdf
World Resources Institute & World Business Council for Sustainable Development, *GHG Protocol: A Corporate Accounting and Reporting Standard: Revised Edition* (p. 116), Greenhouse Gas Protocol Organization, 2004, https://ghgprotocol.org/sites/default/files/standards/ghg-protocol-revised.pdf

WTO, *Principles for the Development of International Standards, Guides and Recommendations,* World Trade Organization (WTO), 2000, https://www.wto.org/english/news_e/news19_e/ddgaw_05dec19_e.htm

Appendix A
Workshop Agenda

SESSION 1: EXISTING & EMERGING LCA STANDARDS

KUMA SUMATHIPALA Oak Ridge National Laboratory	Overview of ISO LCA Standards
DEBBIE STECKEL American Center for Life Cycle Assessment (ACLCA)	Overview of ACLCA LCA-Related Guidance
ALEXANDER FRANTZEN World Resources Institute	Greenhouse Gas Protocol – Scope 3
PHILLIP LUDVIGSEN First Environment	Carbon Accounting and Scope 3 Challenges

SESSION 2: BETTER DATA FOR BETTER RESULTS

JOSH KNEIFEL National Institute of Standards and Technology (NIST)	Why the Details Matter – Assumptions and Uncertainty
REBE FERALDI PNNL & Federal LCA Commons Technical Working Group	Current & Future Status of Federal LCA Commons as Background Data
MATT JAMIESON National Energy Technology Laboratory	Energy Inputs for LCA
HAO CAI Argonne National Laboratory	Transportation Inputs for LCA

SESSION 3: CARBON FOOTPRINTS, BASELINES AND REPORTING

STACY SMEDLEY Building Transparency	Tipping Point: LCA on the Horizon for Decarbonization
KEVIN KIMMEL US TAG to ISO TC207 SubTAG 7	ISO greenhouse gas standards: Where LCA fits in carbon accounting
DANNY MACRI Environmental Protection Agency (EPA)	Enhancing Transparency, Standardization and Reporting Criteria for EPDs

Appendix A. Workshop Agenda

CHAITANYA (CHAIT) BHAT Asphalt Institute	Product Category Rules and Environmental Product Declarations – Guidance for Enhancing Credibility and Allowing Comparability
SANGWON SUH Watershed Technology Inc.	Global Data Comparability and Consistency

SESSION 4: BEYOND THE GATE

CATHERINE HOUSKA Houska Consulting	Beyond the Gate: Performance through End of Life
A. I. (SANDY) WILLIAMSON Williamson Integrity Services Ltd. Calgary	The Role of Corrosion Management in LCA
MIGDALIA CARRION & AUSTIN JARRELL U.S. Federal Highway Administration	Resilience and Sustainability in a Changing World
BARBARA RECK Yale University & REMADE Institute	Reducing the Embodied Carbon of Materials Through Reuse and Recycling: Metals & Plastics
MARK MISTRY Nickel Institute	The Importance of Standards: LCA and Recycling

Appendix B ASTM standards mentioned during the workshop

E60 ON SUSTAINABILITY	**WK90102**	New Practice for Minimum Criteria for Comparing Materials and Systems During Built Environment Use Stage Life Cycle Assessments (LCA) – new work item (precursor to a standard)
	WK90146	Standard Practice for Preparing an Environmental and Human Exposure Screening Report (ESR) for Substances Used in the Built Environment – new work item (precursor to a standard)
	ASTM E3199-22a	Standard Guide for Alternative Allocation Approaches to Modeling Input and Output Flows of Secondary Materials and Related Recycling Scenarios in Life Cycle Assessment
	ASTM E3027–18a	Standard Guide for Making Sustainability-Related Chemical Selection Decisions in the Life-Cycle of Products
	ASTM E2921	Standard Practice for Minimum Criteria for Comparing Whole Building Life Cycle Assessments for Use with Building Codes, Standards, and Rating Systems
	ASTM E3341	Standard Guide for General Principles of Resilience
E54 ON HOMELAND SECURITY	**ASTM E3350**	Standard Guide for Community Resilience Planning for Buildings and Infrastructure

Appendix C ISO standards mentioned during the workshop

ISO 14045 (2012)	Eco-efficiency assessment of product systems – Principles, requirements and guidelines
ISO 14025 (2006)	Environmental labels and declarations – Type III environmental declarations – Principles and procedures
ISO 14021 (2016) + AMENDMENT 1 (2021)	Environmental labels and declarations – Self-declared environmental claims (Type II environmental labeling)
ISO 14026 (2017)	Environmental labels and declarations – Principles, requirements and guidelines for communication of footprint information
ISO/TS 14027 (2017)	Environmental labels and declarations – Development of product category rules
ISO 14040/14044 (2006)	Environmental management – Life cycle assessment – Initial standard, with subsequent amendments to include new annexes and updates.
ISO/TS 14074 (2022)	Environmental management – Life cycle assessment – Principles, requirements and guidelines for normalization, weighting and interpretation
ISO 14044 (2006) + AMENDMENTS 1 (2017) AND 2 (2020)	Environmental management – Life cycle assessment – Requirements and guidelines
ISO 14040 (2006) + AMENDMENT 1 (2020)	Environmental management – Life cycle assessment – Principles and framework
ISO/TS 14072 (2014)	Environmental management – Life cycle assessment – Requirements and guidelines for organizational life cycle assessment – LCA normalization, weighting, interpretation
ISO/TS 14071 (2014)	Environmental management – Life cycle assessment – Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006

Appendix C
ISO standards mentioned during the workshop

ISO/TR 14049 (2012)	Environmental management – Life cycle assessment – Illustrative examples on how to apply ISO 14044 to goal and scope definition and inventory analysis
ISO/TR 14047 (2012)	Environmental management – Life cycle assessment – Illustrative examples on how to apply ISO 14044 to impact assessment situations
ISO/TS 14048 (2002)	Environmental management – Life cycle assessment – Data documentation format
ISO 14046 (2014)	Environmental management – Water footprint – Principles, requirements and guidelines – Water footprint standard, including air and soil emissions information that pertains to aspects of water
ISO 14020 (2022)	Environmental statements and programmes for products – Principles and general requirements
ISO/TS 14029 (2022)	Environmental statements and programmes for products – Mutual recognition of environmental product declarations (EPDs) and footprint communication programmes
ISO 14065 (2020)	General principles and requirements for bodies validating and verifying environmental information
ISO/FDIS 14068 (2023)	Greenhouse gas management and climate change management and related activities – Carbon neutrality – For organizations making claims on “Climate neutral”, “carbon negative”, “carbon free”, “offsetting”, “net zero” claims and related concepts.
ISO 14067 (2018)	Greenhouse gases – Carbon footprint of products – Requirements and guidelines for quantification – Product and service LCA calculation and allocation
ISO 14083 (2023)	Greenhouse gases – Quantification and reporting of greenhouse gas emissions arising from transport chain operations
ISO 14064-1 (2018)	Greenhouse gases – Part 1: Specification with guidance at the organization level for quantification and reporting of greenhouse gas emissions and removals

Appendix C ISO standards mentioned during the workshop

ISO 14064-2 (2019)	Greenhouse gases – Part 2: Part 2: Specification with guidance at the project level for quantification, monitoring and reporting of greenhouse gas emission reductions or removal enhancements
ISO 14064-3	Greenhouse gases – Part 3: Part 3: Specification with guidance for the verification and validation of greenhouse gas statements
ISO 14066 (2011)	Greenhouse gases – Competence requirements for greenhouse gas validation teams and verification teams
ISO/TR 14069 (2013)	Greenhouse gases – Quantification and reporting of greenhouse gas emissions for organizations (guidance for applying ISO 14064-1)

ACKNOWLEDGEMENTS
The authors thank the attendees and speakers who participated in ASTM International's Workshop on Decarbonization: A Gap Analysis of LCA Standards for Industry. Thanks too to ASTM staff Kelly Dennison and Kristy Straiton for their assistance hosting the workshop and Marsha Bischel (Armstrong World Industries, Inc.), William Healy (NIST), and Gonzalo Rodriguez Garcia (NIST) for reviewing the report.

INTERNATIONAL

ADVANCING STANDARDS
TRANSFORMING MARKETS

ASTM INTERNATIONAL HEADQUARTERS

100 BARR HARBOR DRIVE
P.O. BOX C700
WEST CONSHOHOCKEN, PA 19428-2959
USA

Tel +1.610.832.9500

Web go.astm.org