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FOSTERING A CIRCULAR ECONOMY OF MANUFACTURING MATERIALS WORKSHOP REPORT

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Lead Authors

Kelsea Schumacher

Associate, Circular Economy Program
Material Measurement Laboratory
National Institute of Standards and Technology

KC Morris

Systems Integration Division
Engineering Laboratory
National Institute of Standards and Technology

Noah Last[1,2]

[1]Research Associate, Systems Integration Division,
Engineering Laboratory
National Institute of Standards and Technology

[2]Georgetown University

Amy Costello

Armstrong World Industries

Contributing Authors

Buddhika Hapuwatte[3,4], Nehika Mathur[3], Vincenzo Ferrero[3], Maya Reslan[3]

[3]Systems Integration Division
Engineering Laboratory
National Institute of Standards and Technology

[4]University of Maryland

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Executive Summary

A circular economic model is garnering global support across a broad expanse of sectors. The model represents a dramatic transition from the long-employed linear economy (take–make–use–waste) into a regenerative one in which products and materials are kept within the economy through recovery processes including reuse, repair, refurbishment, remanufacturing, and recycling. Cycling materials within the economy not only reduces the demand for raw materials, but also prevents the leakage of materials to unwanted sinks such as the environment, landfills, and incinerators, thereby reducing potential harm to society, the environment, and the economy. Transitioning to a circular economy will further require products to be assessed in terms of not only their function but also their impact on the environment and how well they maintain value. These assessments will need a solid foundation of measurements and practices to bring them to fruition.

Considerable time, thought, and energy is being directed towards enabling this transition. Numerous social, political, and technical strategies are being considered, and to some extent, implemented to affect this necessary change. While the range of organizations participating in these efforts is exceptionally diverse, much of the burden of bringing this vision to a reality will be placed on those who produce goods—i.e., manufacturers. The manufacturing sector transforms materials into products, and hence has a pivotal role to play in assuring that materials are used efficiently and remain in the economy for as long as possible. Manufacturers across sectors and geographic regions are setting environmental, social, and governance (ESG) commitments, including circularity goals, in response to consumer demands, regulations/legislation, and as part of their future planning activities.

Underlying all these efforts is a need for standards to help guide stakeholders, particularly manufacturers, towards synchronized improvements. Standards define basic terminology needed to create a common understanding of shared goals, objectives, and progress. They provide best practices for manufacturers and other sectors to create products that can be recirculated throughout the economy once they reach the end of their useful life. Standard test methods ensure repeatable and comparable procedures for determining properties of materials and products. Further, reporting standards provide a means for documenting environmental, social, and corporate governance (ESG) metrics, and can help to anticipate the problems that lie ahead and where more work is needed.

Towards this end, ASTM International's E60 Committee on Sustainability sought to garner stakeholder input on drivers and barriers facing circular manufacturing and the need for standards to foster a circular economy for manufacturing materials. More specifically, the E60 committee aimed to identify technical standards needed for manufacturers to design and produce products for circularity as well as integrate more diverse feedstocks into production capabilities. Standards are needed to ensure that the outputs of manufacturing operations, both products and by-products, are suitable to re-enter the economy. In this effort, the E60 committee drew on the following sources of information to identify areas where standardization is needed to make substantial improvements to the status quo:

- A survey of manufacturing organizations to understand the current state of the practice towards more sustainable and circular manufacturing approaches,
- A two-day workshop including world-class panelists reporting on current activity supporting circular economy for manufacturing organizations and manufacturing experts who participated in the workshop's roundtable discussions.

The survey and workshop brought to light several key drivers and barriers facing a circular economy and led to the identification of five categories of standards. As shown in **Figure 1**, foundational standards underpin the other standards efforts. Systems-support standards facilitate systems thinking in practice and advance the mechanisms to collect, carry, and provide information throughout the life cycle. The inner boxes in the figure show the types of standards needed in different life cycle phases: front-end design, manufacturing production, back-end recovery, and recycling-related standards. More specifics of the needed standards and their focus areas are described in greater detail in this report. Successfully implementing the identified standards will assist with ensuring trustworthy and reliable material streams for future manufacturing.

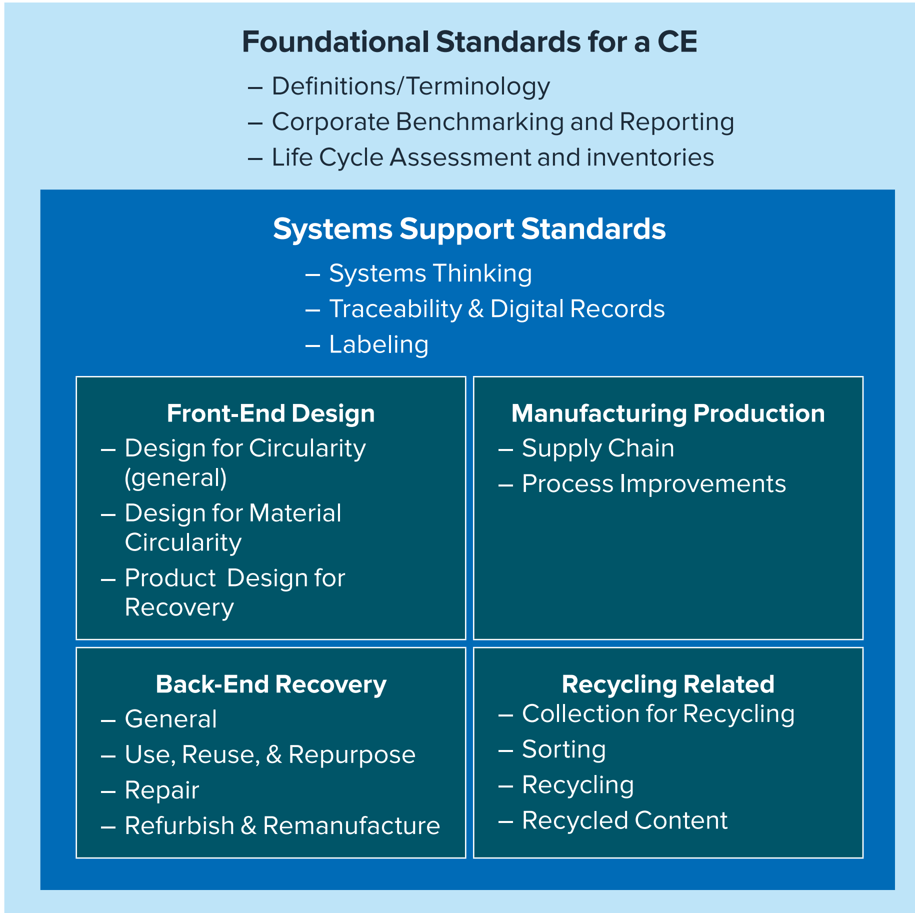


Figure 1 Standards areas identified through manufacturing survey and workshop

This report and the types of standards it proposes will be of particular interest to material and product designers, manufacturing processors, recovery processors (including those in the resale, repair, repurpose, refurbish, remanufacture, and recycling sectors), as well as system planners and policymakers. These stakeholders will also be critical for realizing these CE standards. ASTM Subcommittee E60 is initiating new efforts to address some of the standards needs and welcome other experts in the field to join and expand upon existing development activities and initiate new ones.

In addition to the standards identified, two key takeaways stemmed from the survey and workshop: first, participants have a transformative, though fragmented, vision for a new way of thinking about how materials are created and used that is regenerative rather than extractive. Second, participants are motivated to make this vision a reality, and they are indicative of broader desire across the manufacturing sector to implement circularity. ASTM E60 is well-suited to play a part in developing and coordinating standards that foster a circular economy for manufacturing materials.

List of Acronyms

ASTM	American Society for Testing and Materials
CE	Circular Economy
DfC	Design for Circularity
EoL	End-of-Life
GHG	Greenhouse Gas
HDPE	High-density polyethylene
KPI	Key Performance Indicator
LCA	life cycle assessment
MFA	material flow analysis
NIST	National Institute of Standards and Technology
OEM	Original equipment manufacturer
PET	Polyethylene terephthalate
SDO	standards development organization
SMMs	Small and Medium Manufacturers
UN	United Nations

1 Introduction

Interest and efforts to transition away from a linear—take, make, use, discard—economic model and toward a more circular economy (CE) have increased significantly in recent years. A CE aims to keep products and materials in the economy—and out of unwanted sinks such as landfills, incinerators, and the environment—for as long as possible through *recovery processes* including reuse, repurpose, repair, refurbishment, remanufacturing, and recycling. The manufacturing sector is especially vital in facilitating the transition to a CE: not only are they responsible for production operations and resource use therein, but manufacturing firms also make key decisions regarding material and product design, sourcing, procurement, and assembly. Together, these have a profound impact on the feasibility and practicality of employing circular practices. However, improving the ability of manufacturers to foster a CE requires consensus-based industry standards to support harmonization, consistency, reliability, and ultimately build trust within the marketplace.

Several international and national standards bodies are developing CE-related standards and each brings a different perspective. ASTM International (here after referred to as ASTM) is an international standards development organization (SDO) well known for publishing consensus-based technical standards for a wide range of materials, products, systems, and services. The scope for ASTM E60 on Sustainability includes supporting other ASTM committees in developing sustainability-related standards. The ASTM Subcommittee E60.13 on Sustainable Manufacturing sets standards around manufacturing, particularly standard guidance and methods for process improvement, decision making for sustainable investments, and more. The International Organization for Standardization (ISO) is perhaps the leading international organization developing management standards that will be instrumental to supporting a CE. The new ISO Technical Committee (TC) 323 on Circular Economy will provide principles and a framework for how to define and manage CE globally. ASTM Subcommittee E60.13 coordinates the U.S. Technical Advisory Group (TAG) to ISO/TC 323 to design CE management standards.

ASTM Subcommittee E60 is positioned to address many of the standardization needs to foster a CE. Enabling this transition requires engagement and input from the manufacturing sector to identify specific standards that would be useful to facilitate circularity. To support this, the committee undertook a two-part initiative to determine the standards needed to facilitate manufacturing in the CE. First, the committee surveyed manufacturers in the U.S. and beyond to collect information on the status and challenges associated with manufacturing in a CE. Second, the committee hosted a two-day virtual workshop titled “Fostering a Circular Economy of Manufacturing Materials” in April 2022. The workshop convened manufacturers and other stakeholders from across a variety of sectors to discuss challenges to manufacturing in a CE and ways that standards can help overcome barriers, as well as to identify needs for specific standards. Information from the survey was compiled with that from the workshop to identify categories of standards needs for manufacturing in a CE.

This report presents the key takeaways from the manufacturing survey, key outcomes from the workshop, and next steps for addressing the standards needs identified in both. Section 2 provides the background for manufacturing in a CE, including the role of standards in relation to policy; it also provides context for circular manufacturing relative to other sustainable manufacturing concepts, such as lean and zero waste. Section 3 then presents key takeaways from the *Manufacturing Circular Economy Survey* regarding current sustainable and circular manufacturing practices and opportunities for new standards. Section 4 introduces the workshop and provides a summary of each session. The outcomes of the workshop and survey are discussed in Section 5, framed as key drivers for and barriers facing circularity in manufacturing. Section 6 provides a series of standards identified through the survey and workshop outcomes, categorized into foundational, system support, and life cycle phases. The final section outlines next steps for ASTM and other stakeholders to produce the types of standards identified in Section 6 to support manufacturers across the sector in the effective and efficient transition to a CE.

2 Background and Motivation

A circular economy (CE) has been proposed as an alternative economic model to the current linear—take, make, use, discard—model that presides today. The need to transition to a CE is driven by climate change, limited natural resources, a growing global population, and rising middle classes in emerging economies (Morris 2022). Stakeholders around the world are calling for more sustainable systems, including young people—the future generations (e.g., Fridays for Future, the Sunrise Movement), governments (e.g., United Nations Sustainable Development Goals, United Nations Environmental Programme), industry (e.g., U.S. Plastics Pact), and investors (e.g., Task Force on Climate-Related Financial Disclosures).

A CE is defined as "an economy that uses a systems-focused approach and involves industrial processes and economic activities that (A) are restorative or regenerative by design; (B) enable resources…to maintain their highest values for as long as possible; and (C) aim for the elimination of waste through the superior design of materials" (Sullivan 2020). As such, a CE aims to keep materials and products within the economy—and out of landfills, incinerators, and the environment—through design for and implementation of a range of end-of-life (EoL) alternatives including recovery processes. Figure 2 displays how these mechanisms can close the life cycle of products and materials. Inner circles should be prioritized as they maintain the current value of materials longer, provided that they require less energy and resources to process. Not shown in the figure are emerging recovery technologies such as anaerobic digestion and pyrolysis.

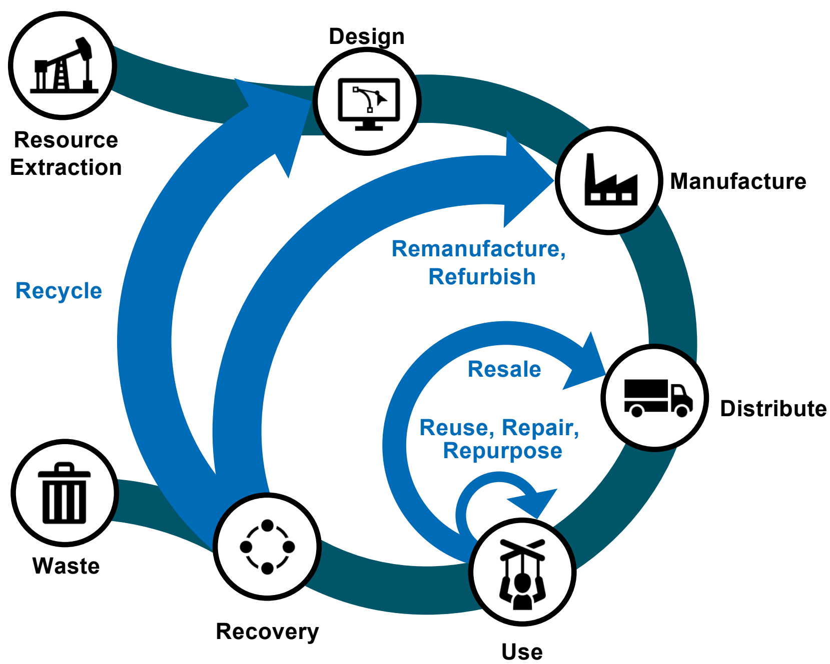


Figure 2 Circular economy system diagram displaying several major mechanisms to close the life cycle of materials and products

Such a model decouples economic growth from environmental degradation by improving resource efficiency and decreasing material use, energy consumption, and waste production (Nasr 2022; Romero and Rossi 2017). Further, a CE paradigm supports sustainable development by using resources more efficiently and allocating them (and waste streams) more equitably, thus helping to address problems like resource scarcity, climate change, biodiversity loss, and environmental justice (Gaustad et al. 2018; Halog and Anieke 2021; Nadeem et al. 2019; van Loon, Delagarde, and Van Wassenhove 2017). As the world's driver of resource use and economic activity, the manufacturing sector is integral in the transition to the CE.

2.1 Manufacturing in a Circular Economy

The manufacturing sector supports development and feeds, clothes, and shelters our world's growing population (Frosch and Gallopoulos 1989). The sector thus comprises establishments—including plants, factories, and mills—engaged in the transformation of materials or substances into new products (Bureau of Labor Statistics 2020). Manufacturing establishments are often described in terms of size classes, including small (1–49 employees), medium (50–249), and large (250+). The U.S. has a large number of small and medium-sized manufacturers (SMMs): nearly 250,000 in 2019 (US Bureau of Labor Statistics 2022). By total number, SMMs make up roughly 98.6 % of American manufacturing companies, generating roughly 11.6 % of the U.S. economic output, and employing 8.5 % of the U.S. workforce (Caplan 2020).

Currently, most manufacturers operate using a linear economic system in which resources are extracted from the earth, processed into the building blocks of products, assembled into finished goods, and distributed around the globe. At the end of their desired or useful life, products are typically landfilled or incinerated. Transitioning to a CE model will keep products, and their component materials, in the economy and maintaining value for longer, thereby reducing material extraction and waste generation while supporting long-term economic resilience (Figge et al. 2018; Romero and Rossi 2017; Tai 2022). The CE supports U.S. economic development by improving supply chains, strengthening domestic manufacturing, increasing product value throughout the product's life cycle, and minimizing the life cycle impacts of products (Carpenter, 2022).

Manufacturers have perhaps the most influential role of any stakeholder in facilitating the transition to a CE. Not only are manufacturers responsible for production operations and resource use therein, but manufacturers also make key decisions regarding material and product design, sourcing, procurement, and assembly, which together have a profound impact on the feasibility and practicality of employing the circular practices depicted in **Figure 2**. The ability of a product to be recovered at end-of-use is often determined during the design phase of the product. Further, supporting recycling markets requires manufacturers to utilize feedstock with recycled content, including recycled material from both post-consumer discards (generated by the consumer after use) and/or post-industrial discards (generated during a manufacturing process, also referred to as pre-consumer). Finally, the transition to a CE will require digital records to trace significant information about products such as material composition and conditions from the use phase of the life cycle. The creation and maintenance of these records will need to be incorporated into design and production.

2.1.1 Environmental Impacts of Manufacturing

Improving resource efficiency is key to a CE. Efficiency entails not only reducing waste generation during the manufacturing process but circulating end-of-use products and materials back into new goods. Manufacturers may produce hazardous and/or non-hazardous waste. The former is tightly regulated and therefore the volumes, characteristics, and treatment of that waste stream are well documented (discussed further in Section 2.2). CE efforts discussed in this report primarily pertain to non-hazardous material discards and the need to reduce waste streams and create new feedstocks of recovered materials. Because they are non-regulated and diverse in nature, non-hazardous industrial waste streams are poorly understood. To date, little attention has been given to tracking the flows of material discards from manufacturers and accounting for the recycling of industrial materials is nearly non-existent. Recovery of materials can include reuse and recycling of discards into new feedstocks.

The need to transition to a CE extends beyond material flows, as resource use and greenhouse gas (GHG) emissions are intricately interconnected. In fact, research from the Ellen MacArthur Foundation shows that switching to entirely renewable energy today would only get us 55% of the way to net zero carbon emissions (Ellen Macarthur Foundation 2021; Nasr 2022). In addition, the United Nations Environmental Programme's (UNEP's) International Resource Panel estimates that over 50% of global GHG emissions and 90 % of global biodiversity and water stress impacts can be directly linked to the way we extract, use and dispose of material resources in our consumption and production systems (IRP 2020).

Manufacturers directly and indirectly generate GHG emissions. The direct emissions, so called "Scope 1 emissions," are generated directly from company facilities, such as company facilities and vehicles. Indirect emissions are those associated with the production of the company's electricity, heat, steam, and cooling use (Scope 2) and those generated through the value chain (Scope 3) which includes both upstream (e.g., capital goods, purchased goods, and services) and downstream (e.g., use and end of life treatment of products) (Greenhouse Gas Protocol 2001; World Resources Institute and World Business Council for Sustainable Development 2004). Globally, manufacturing accounts for 12% of GHG emissions (Nasr 2022). However, according to the EPA, in 2019 manufacturing accounted for 23 % of direct (Scope 1) GHG emissions in the U.S. (EPA, 2022). The built environment (e.g., buildings and infrastructure) contributed 38% of energy-related CO_2 emissions globally in 2019 (Bezpalko 2022; United Nations Environmental Programme 2020); this includes the construction and operations of buildings, both of which use manufactured products. These values increase significantly when indirect (Scope 2 and 3) emissions are included (Hertwich and Wood 2018).

Manufacturing and material use are indispensable for development, but without serious reassessment, the negative impacts of the current linear economic model will continue to increase. The UNEP's International Resource Panel predicted potential environmental impacts expected by 2060. **Table 1** depicts "Business as Usual" impacts (based on 2015 levels) in relation to potential impacts aligned with achieving the UNEP's Sustainable Development Goals (SDGs). The SDGs are designed to support equitable global development while minimizing environmental impact (IRP 2020; Oberle et al. 2019).

Business as Usual	Achieve UNEP SDGs
↑ >**2X** global material extraction	↓ **25%** resource extraction
↑ **43%** GHG emissions	↓ **90%** GHG emission
↓ **20%** natural habitats	↑ **10%** forest and natural habitats
	↑ **8%** global GDP

Table 1 Comparison of environmental impacts under "Business as Usual" predicted by 2060 relative to 2015 levels, and impacts if we achieve the UNEP's proposed Sustainable Development Goals (SDGs) (Oberle et al. 2019)

In response, some manufacturers and their stakeholders have begun transitioning to less wasteful, more resource and energy efficient operations across their supply chains (Escoto, Gebrehewot, and Morris 2022). Manufacturing companies are also making pledges to support a CE through triple bottom line (TBL) initiatives (social, environmental, and financial) and environment, social, and governance (ESG) commitments in response to consumer demands and other factors (Escoto, Gebrehewot, and Morris 2022). In many cases, these pledges involve intra-industry cooperation. For example, the US Plastics Pact is an agreement by producers and original equipment manufacturers (OEMs) across a range of industries to work across the plastic packaging value chain to create a circular economy for plastics and eliminate unnecessary plastics (US Plastics Pact 2021). Their "Roadmap to 2025" set several goals for their members, including making 100% of their plastic packaging reusable, recyclable, or compostable and making an average of 30% of their plastic packaging from recycled content or responsibly-sourced, biobased content. According to Reuters, $649 billion was placed into ESG funds in 2021—the greatest such investment to date (Kerber and Jessop 2021). However, few regulations exist regarding ESG funds. Thus, whether this money is directed to companies that support efforts towards decarbonization or circular economy is currently unverifiable, but this number certainly reflects the growing demand for sustainable investments. In addition, new policies are suggesting that governments are also taking the transition seriously. Several recent Executive Orders from the U.S. Government have aimed to strengthen America's supply chains, revitalize domestic manufacturing, and support domestic recycling and reprocessing of minerals (see Section 2.2 for more on the policy landscape) (The White House 2020; 2021). Similar activity is taking place elsewhere around the world as well (e.g., The State Council, People's Republic of China 2021; European Commission 2020a; Government of Canada 2020).

2.1.2 CE in Context

The CE approach fits directly into the more general ideals of sustainable development, which the UN has defined as “development that meets the needs of the present, without compromising the ability of the future to meet their own needs” (United Nations 1987). Sustainable manufacturing is a holistic approach that incorporates environmental, social, and economic (i.e., TBL) considerations into manufacturing. As such, sustainable manufacturing involves the creation of products through economically sound processes that minimize negative environmental impacts and conserve energy and natural resources (US EPA 2015). Sustainable manufacturing also aims to enhance employee and community safety through trustworthy practices. Circular manufacturing is one of multiple strategies to support more sustainable manufacturing that is based on the philosophy of keeping materials circulating within the economy. Other strategies for sustainability, such as zero waste, cradle to cradle, and lean manufacturing, have largely developed and operated independently of one another, yet taken together, they can be synergistic and support sustainable development.

Some of the discussion in this report refers to sustainable manufacturing broadly and some more specifically to circular manufacturing. Industry, government, and academia have pursued sustainable manufacturing for longer than the discussion of CE although the two are not mutually exclusive. More information and awareness of sustainable manufacturing exists than for CE or circular manufacturing. Additionally, sustainable manufacturing has largely been driven by the academic and operations communities—which strive for practical reductions in resource use from an operational perspective. CE, on the other hand, is being driven by the business community and aims to make systemic changes to business-as-usual.

2.2 Policy Approaches

In the past, regulations and standards were implemented in response to mitigating the various deleterious effects of production and consumption. In most countries around the world, local governments, not federal ones, are responsible for the management of non-hazardous waste, creating a decentralized system for waste management (Kaza et al. 2018). In the U.S., most federal regulation around resource use, recycling, and waste management is authorized through the Resource Conservation and Recovery Act (RCRA) (US Environmental Protection Agency 2021) and the Save Our Seas 2.0 Act (SOS 2.0) (Sullivan 2020). The former categorizes waste management into hazardous and non-hazardous solid waste. The RCRA gives the U.S. Environmental Protection Agency (EPA) the authority to control hazardous solid waste from “cradle to grave” (e.g., transportation, generation, treatment, storage, and disposal). It also sets minimum requirements for waste collection and non-hazardous solid waste landfilling specifications. The law gives state, local, and tribal governments the authority to regulate non-hazardous waste. The law does not clearly distinguish recycling from other non-hazardous waste management, and only defines certain hazardous wastes as recyclable (e.g., materials that are considered a valuable commodity). No authority is given to the federal government on the management of products or materials, resulting in a lack of uniformity in recycling efforts across the U.S. This dependency in local and regional markets has led to fragmentation of the recycling industry and inconsistencies in materials/products recovered for recycling across the nation (Wagger 2022).

Other parts of the world have similar regulatory approaches to manage waste. For example, in Japan, solid waste is managed by municipalities whereas the European Union (EU) has policies around solid waste management, but each member defines and implements regulations locally (Gusmão Gomes de Andrade Lima et al. 2016).

Extended Producer Responsibility (EPR) laws are one approach increasingly being implemented around the world to facilitate material recovery and recycling. Under EPR, a producer’s responsibility for a product is extended through the post-consumer stage of the product’s life cycle, thereby making producers responsible for EoL management of products while simultaneously incentivizing them to design more durable and recyclable goods (OECD 2001). EPR has been implemented for various product streams (e.g., electronics, batteries, packaging) across the EU (European Commission 2008), Japan (Ogushi and Kandlikar 2007), Canada (Hickle 2013), as well as select U.S. states (ACA 2022; Allen et al. 2022; Cutter, Priola, and Gonzales 2022; Perez 2010; Representative Janeen Sollman and Senator Michael Dembrow 2021; Representative Nicole Grohoski 2021; Electronics TakeBack Coalition n.d.; PaintCare Inc. 2022).

In addition, policies are being implemented to ensure that the manufacturers are held accountable for environmental and CE pledges. Financial regulators are making recommendations and rules for companies to produce sustainability reports that are accurate and comparable across companies. For example, in 2002 the U.S. Securities and Exchange Commission released a proposed rule that public companies must include climate-related disclosures in their reports to stakeholders and the Commission, including how their company contributes to and may be affected by climate change (US Securities and Exchange Commission 2022). Brazil's central bank (Mandl 2021), the Singapore Exchange (Reuters 2021), and the Council of the European Union (Council of the European Union 2022) have established similar rules.

In summary, regulations for EoL recovery are increasingly being proposed and implemented, however, they remain limited and those that exist are fragmented. Little consistency exists across regions, and even less across countries. Existing and proposed EPR strategies are also a patchwork with limited consistency and harmonization. That said, financial regulators around the world are seeking a common approach for corporate sustainability reporting.

2.3 The Role of Standards

Standards provide harmonized, repeatable, and accepted guidelines, rules, or characteristics for activities that aim to achieve order in a given context (ISO/TMBG Technical Management Board 2004; International Organization for Standardization and International Electrotechnical Commission 2019). Standards can either be physical or documentary; the former, referred to as Standard Reference Materials (SRMs), are stable and homogenous materials with respect to specified properties established to verify measurement results, develop new measurement methods, and provide users with the means to establish traceability of their results to a stated reference (National Institute of Standards and Technology 2010; 2022). Documentary standards are established by consensus and approved by a recognized body. They generally contain definitions, technical specifications, or other criteria designed to be used consistently by stakeholders, thus increasing the reliability and effectiveness of goods and services. Unless otherwise specified, the term 'standards' from here on will refer to documentary standards. **Table 2** provides common types of documentary standards. The definitions in this table are consolidated from (MachineDesign 2015; Piping Engineering 2017; Global Reporting Initiative 2022; ASTM International 2022a).

Standards can be initiated at different organizational levels (e.g., global, country, or company) and are typically developed by bringing together relevant stakeholders to develop normative requirements, which are then approved by consensus through a recognized body (Ellen MacArthur Foundation 2019). Most standards relevant to a CE are voluntary consensus standards, meaning they are developed in cooperation with all parties with an interest in the standard and that compliance is not regulated or mandatory. That said, voluntary consensus standards carry significant weight, as they may be adopted widely and openly, written into contracts, agreements, and used to create federal policies and laws (Morris 2022).

The development of open, consensus-based standards is critical in the transition to a CE, especially to manufacturers. Harmonization and normalization of circular metrics, methods, tools, and practices is needed to support information and data sharing, market stability, and integrity across supply chains and to consumers. Currently, although the CE is gaining support and being implemented by the manufacturing sector, we lack consensus among businesses and governments on how to interpret circularity and which metrics to use to measure its success (Levy 2022). Standards are critical in the transition to a CE to demonstrate regulatory compliance or fill regulatory gaps, increase transparency and trust among stakeholders and consumers, as well as support market development (Tassey 2000; European Commission 2022).

Types of Documentary Standards	Description
Terminology	Contain definitions of terms and explanations of symbols, abbreviations, and acronyms.
Guides	Collections of information or series of options that do not recommend specific courses of action. They generally inform people of the knowledge and approaches being taken in given subject areas.
Practice Methods	Instructions for performing one or more operation that does not generate a test result. Examples include application, assessment, cleaning, collection, inspection, preparation, sampling, and training.
Classifications	Systematic arrangements or divisions of materials, products, systems, or services into groups based on similar characteristics such as origin, composition, properties, or use.
Specifications	Requirements that must be met by a material, product, system, or service. The specification identifies test methods for determining whether each requirement is met. These requirements can include physical, mechanical or chemical properties, and safety, quality or performance criteria.
Test Methods	Defined procedures that generate test results. Examples include identification, measurement, and evaluation of one or more qualities, characteristics, or properties.
Reporting Metrics	Standard description of what an organization should be doing or reporting (e.g., Global Reporting Standards).
Codes	Descriptive standards, especially safety-related, that are often adopted into laws (e.g., ASME B31 codes for pressure piping).
Corporate standard operating procedures (SOPs)	A description of standard procedures for operations that are based on industry or company-specific best practices and laws.

Table 2 Common Types of Documentary Standards

2.3.1 **Informing, Implementing, and Bridging Regulation**

Standards can help manufacturers follow existing regulations and bridge regulatory gaps, as well as support governments in crafting effective new regulation. The variability of regulations at local, state, national, and international levels is a challenge for manufacturers. Standards can help provide consistency across the various levels to address differences associated with different policies. Additionally, standards can be developed to demonstrate regulatory compliance where laws and regulations are imprecise. For example, standards focused on circular design can help producers follow and implement EPR laws. Design standards can further clarify adherence to a set of mandatory or voluntary levels of performance.

Standards can also bridge regulatory gaps. In this sense, standards can support unification and harmonization across industry by establishing definitions, specifications, and best practices that federal and/or state legislation currently does not address. Such harmonization could bolster domestic recycling in the U.S. by establishing consistencies across regions and states that the federal government does not have the authority to address. Additionally, some aspects of the CE are not suitable or ready for regulation, yet require standards to foster development. Standards can play a role in supporting and increasing economic momentum or technological advancement where legislation may thwart innovation. For instance, standards would be useful to support the recycling of materials and products that are economically viable as commodities, whereas legislation may be better suited for more difficult-to-recycle materials.

Additionally, standards can open opportunities for regulation and help guide governments in crafting regulation by providing much of the technical detail and requirements necessary to make good policy. They can also reduce barriers by providing an established common language and approach. In the CE realm, the goal is to develop proactive standards that governments can incorporate into legislation. For example, policies can coordinate what information should be documented in corporate sustainability reports based on standardized methodologies to produce verifiable and comparable environmental claims. Ultimately, facilitating a transition to a CE necessitates the careful design and implementation of both policy and standards. Tecchio and colleagues suggest that a framework of standards coupled with appropriate policy will help the European Union achieve the material efficiency goals in its roadmap to 2050 (Tecchio et al. 2017).

2.3.2 **Transparency and Trust**

Consensus-based, industry-wide standards can also facilitate transparency and trust across the CE and thereby increase consumer confidence in goods and services. This includes consumers within and across the product value chain. Environment-based financial disclosures, pledges, and green claims are a particular area where standards are needed to maintain consumer trust by establishing rules regarding how to make claims in the market. For example, standard metrics and methodologies are necessary to ensure company environmental impact assessments are consistent, reliable, and verifiable and to certify that resulting “green” claims can be substantiated. One major component to this is ensuring that materials are traceable so that sustainability claims can be corroborated (e.g., Mass Balance accounting for products that claim to contain recycled plastic (Beers et al. 2022)). Certification programs with labeling schemes can attest that standards have been followed and effectively convey an accurate message to consumers. Several such certifications exist today aimed at improving the sustainability of supply chains and products (e.g., Better Cotton Initiative, 2022; Cradle to Cradle Products Innovation Institute, 2022; Energy Star, 2022; EPEAT, 2022; FairTrade International, 2022; Forest Stewardship Council, 2022). Finally, reporting organizations create standards for assessing and reporting on environmental impacts and progress towards sustainability goals. Companies then use them for disclosures to the public and regulators in documents such as sustainability reports, financial filings, and advertisements (e.g., ASTM Subcommittee E.50, Sustainability Accounting Standards Board (SASB), Global Reporting Initiative (GRI)).

2.3.3 **Support for markets and development**

Standards help manufacturers develop and create markets for their products by coordinating consensus on definitions, specifications, and best practices (Levy 2022). International standards are especially important because many manufacturing supply chains are global in nature. Consensus-based standards support equity between large and small companies and developed and developing countries by leveling the playing field (Levy 2022). This keeps competition strong, thus lowering prices and encouraging innovation. In addition, the goal of a resilient economy is not necessarily using less, but rather maintaining a steady supply and demand, for example, by increasing circularity (Tai 2022).

The plastics industry is a good example of how standards help develop markets. There are many standards for measuring the properties of virgin plastics, but very few for recycled "virgin-equivalent" (structurally and functionally the same as virgin) and "near-virgin" (very similar to virgin) (Tara Immell et al. 2020). Several standards do exist that support the recycled plastics industry. For example, *CEN EN 15343: Plastics — Recycled Plastics* standard provides best practices for recycled content and traceability so procurement professionals can confirm that plastics that are marketed as recycled are indeed recycled. *ISO 14026:2017, Environmental labels and declaration*s is a standard for labelling the environmental impact of materials, including recycled plastics, and can be used for verification. ISRI's *bale specifications* serve as standards that procurement professionals can use to ensure the quality and source of bales of recycled plastics (DeCaria 2022; Wagger 2022). However, many gaps in standards across the plastics supply chain still exist, preventing markets around recycled plastics from growing and stabilizing (Tara Immell et al. 2020). Gaps include simple terminology standards that define virgin-equivalent and near-virgin plastics, standards for best practices for mechanical and non-mechanical recycling (e.g., chemical recycling), and standards for minimum performance requirements for recycled resin (Tara Immell et al. 2020). Informal recyclers (sometimes called "waste pickers") are also pivotal for recycling markets, and standards will support this group by stabilizing the markets for recyclables (Simon et al. 2021).

2.4 **The Life Cycle Approach to Developing Standards for a CE**

As indicated previously, there is significant effort within the standards realm to support the transition to a CE. Several studies and reviews have argued that a patchwork of standards, policies, and technologies will be insufficient, and that we need a holistic approach to implement the CE into the manufacturing sector (Bjørnbet et al., 2021; Wang et al., 2018). Standards will be key to forming this holistic approach. We need a similarly broad and comprehensive framework of standards that aligns with other sustainable manufacturing efforts (Reslan et al., 2022a).

A holistic way to approach manufacturing standards for a CE is to identify the standards needed across the product life cycle, from the material acquisition and design stages to the product EoL and recovery of materials for use in new products. This method emphasizes the need for a systems approach to CE and highlights why standards are necessary not only for products and procedures, but also for the information and materials that flow across the product life cycle(Reslan et al. 2022). Recall **Figure 2**, which shows the life cycle of a product in a CE, in which all the loops represent material remaining in the economy. For materials to effectively recirculate back into the economy, however, requires a litany of information that must be considered at each stage of the life cycle. For example, designers should consider market data when designing a product, and may have certain constraints such as regulations, company policies, standards, and government incentives. They must also consider the mechanisms to use for designing (e.g., software tools like CAD/CAM) and their own company's Design for Circularity goals (DfC: e.g., design for recovery) (Ferrero, Hapuwatte, and Morris 2022).

Standards are pivotal for ensuring that the information flows across the product life cycle are useful, reliable, and traceable. The increased trend of automation and data exchange in manufacturing processes (i.e., Industry 4.0) and the emergence of Smart Manufacturing Systems have taught us that standards are necessary not only for instructing workers in domains across the manufacturing sector (e.g., designers, builders, decision makers), but for facilitating the transfer of information across those domains (Lu, Morris, and Frechette 2016). Thus, standards are necessary for each stage of the product life cycle and for the information flows between those stages. For example, when a designer is considering which material to use in a product, they must consider how and from where the material is sourced, whether manufacturers in the supply chain are equipped to use that material, how long the overall product will last using that material, and what will happen to the material at the end of the product's life. Standards for material quality and sourcing will facilitate the decision-making process. In a CE, the designer has additional considerations. For example, circular design entails choosing recycled or refurbished material that has already been used multiple times. Standards are necessary to ensure that this material both is of sufficient quality for the product's use phase, and that it will be recoverable at the end of the product's life.

2.5 Circular Economy Standards Landscape

Existing standards that address the transition to a CE for manufacturing can be divided into three categories as displayed in **Figure 3** (Escoto, Gebrehewot, and Morris 2022). Note that these standards are coming from different perspectives and efforts that are working in parallel. Policy experts, managers, and scientists are concurrently pushing forward the work towards transitioning to a CE. For the transition to succeed these efforts must take hold within individual manufacturing organizations as new forms of standard practice. *Goal Setting* (bottom left) organizations inform and set direction for the development of CE standards by supporting the coordination across governments, industries, and investors (Reslan et al. 2022). Current work in this area comes from the UNEP's SDGs, the Greenhouse Gas (GHG) Protocols (Greenhouse Gas Protocol 2001), and the Sustainability Standards Accounting Board (SASB) (Sustainability Accounting Standards Board 2018), among others. *Management Standards* create best practices and frameworks for CE standards. ISO is a leading international organization developing management standards, many of which can help to address CE goals. The ISO Technical Committee (TC) 323 on Circular Economy will provide principles and a framework for how CE will be managed and discussed globally. Finally, Measurement Standards organizations, like ASTM International, use measurement science expertise to create documentary standards, specifications, and procedures.

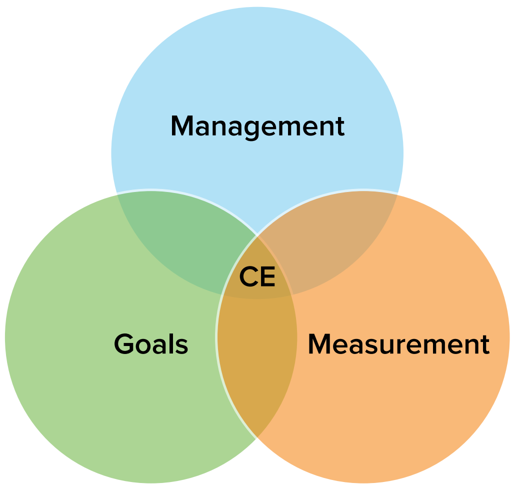


Figure 3 Three categories of standards that support manufacturing in a circular economy

2.5.1 Goal Setting

In 2015, the United Nations Members States adopted a blueprint for global development through 17 Sustainable Development Goals (SDGs) (**Figure 4**) and 169 targets. The SDGs aim to eliminate poverty and improve quality of life in a manner that is sustainable for future generations (United Nations 2015). A CE is being recognized as a promising avenue for achieving a variety of these goals, especially SDG 12 (Responsible Consumption and Production). ISO/TC 323 on circular economy maintains that CE broadly contributes to SDGs 1-16 (International Organization for Standardization 2018a). But other UN-affiliated institutions suggest that a CE will support select SDGs more specifically (highlighted in **Figure 4**) (Berg et al. 2018; United Nations General Assembly and ECOSOC Joint Meeting 2018).

Figure 4 United Nations Sustainable Development Goals highlighting CE-related goals (adapted from United Nations, 2015)

2.5.2 Management Standards

The International Organization of Standardization (ISO) has a suite of management standards that support sustainable manufacturing practices (**Table 3**). ISO standards are international agreements approved by representatives through consensus, and thus represent internationally-recognized best practices for their fields. The organization is comprised of a global network of 167 national standards bodies which represent ISO members. These members are the foremost standards organizations from individual countries, and there is only one member per country; thus, each member in turn represents ISO within its own country. The U.S. is represented by the American National Standards Institute (ANSI). ISO standards are developed by groups of experts called technical committees (TCs) which are put forward by the national members. ANSI therefore serves as an apex SDO that collates findings from domestic Technical Advisory Groups (TAGs), and then appoints delegations to represent U.S. interests at ISO/TCs.

Standard Title and *Responsible ISO/TC*	Description
ISO 9000: Quality Management *ISO/TC 176*	Series of standards that describes the fundamental concepts and principles of quality management systems for manufacturing and service industries (International Organization for Standardization 2015b).
ISO 14000: Environmental Management *ISO/TC 207*	Series of standards that help organizations minimize the environmental impact of their operations. Specifies requirements for the development and implementation of environmental management systems (International Organization for Standardization 2015a; ISO 2019).
ISO 50001: Energy Management *ISO/TC 301*	Specifies requirements for establishing, implementing, maintaining, and improving an energy management system (EnMS) (International Organization for Standardization 2018b).
ISO 20140: Evaluating energy efficiency and other factors of manufacturing systems that influence the environment *ISO/TC 184*	Provides principles and guidelines for the evaluation of energy efficiency and other factors of manufacturing systems that influence the environment (International Organization for Standardization 2019).

Table 3 Existing ISO Standards that Support Manufacturing in a CE

In parallel, the ISO/Technical Committee (TC) 323 works in cooperation with other existing committees on subjects that may support standards efforts related to the circular economy. As shown in **Figure 5** the US Technical Advisory Group (TAG) for ISO/TC 323 reports to ASTM International E60 Committee on Sustainability. The U.S. TAGs serve as mirror committees to the ISO Technical Committees at the national level. The U.S. TAG to ISO TC 323 comprises the five mirror working groups at the national level. The main function of the U.S. TAG is to designate U.S. experts to the ISO working groups, develop U.S. consensus on topics that arise during the standards development process, submit ballot comments, and cast the U.S. vote. (National Institute of Standards and Technology 2021).

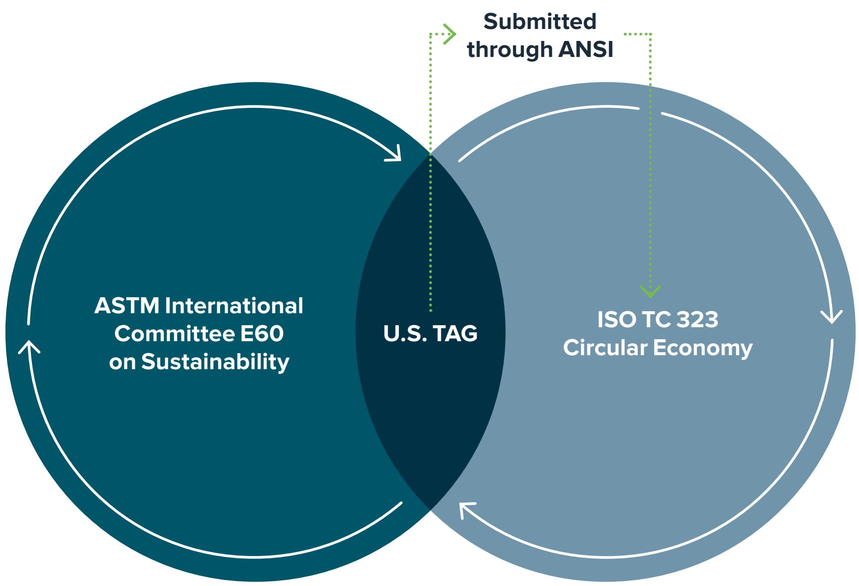


Figure 5 Organizational overview of U.S. engagement with ISO/TC 323.

Table 4 describes the five working groups for the U.S. TAG of ISO/TC 323 on Circular Economy. Each working group is currently developing a standard on the topical area. Stakeholders working on these groups include governments, industries, and enterprises from around the world.

Working Group	Focus Area
1: Terminology, principles, frameworks, and management system standard	– Identifying CE-related terms and providing technical definitions.
2: Practical approaches to develop and implement Circular Economy	– Collating business case studies that are implementing CE. Identifying their challenges and successes. – Framework for organizations to develop CE business models.
3: Measuring and assessing circularity	– Identifying metrics to measure and quantify CE (value-based, LCA-based, etc.). – Working to harmonize the most relevant metrics. – If possible, will identify/develop one metric that captures the measure of CE.
4: Circular Economy in practice: experience feedback	– Performance-based approach for CE (Economy of Functionality and Cooperation). – Definitions and concepts to help analyze and evaluate case studies from a triple-bottom line perspective.
5: Product circularity data sheet (PCDS)	– Developing a PCDS, a standardized document that enables the digital exchange of data related to circularity characteristics of products across supply chains. – The PCDS aims to facilitate data related to circularity characteristics to support standardization and transparency.

Table 4 The five working groups for the U.S. TAG of ISO/TC 323 on Circular Economy. Each working group is currently developing a standard on the topical area. Stakeholders working on these groups include governments, industries, and enterprises from around the world (International Organization for Standardization 2018b; National Institute of Standards and Technology 2021).

2.5.3 **Measurement Standards**

ASTM International has expertise and structure to support the development of measurement-focused documentary standards for a CE. ASTM is independent of ISO, and similarly develops voluntary consensus-based standards. Currently, more than 12,000 ASTM standards are used around the world to "improve product quality, enhance health and safety, strengthen market access and trade, and building consumer confidence" (ASTM International 2022c). Like ISO, technical committees develop and maintain ASTM standards. ASTM committees are comprised of volunteers from industry, including manufacturers, consumers, government, and academia. Any interested individual can participate in ASTM TCs through ASTM membership.

Each technical committee in ASTM is composed of subcommittees that address specific segments within the general subject area covered by the technical committee. ASTM Committee E60 on Sustainability was formed in 2008 and as of 2022 is composed of the following technical subcommittees:

- E60.01 Buildings and Construction
- E60.07 Water Use and Conservation
- E60.13 Sustainable Manufacturing
- E60.21 Terminology
- E60.80 General Sustainability Standards

The scope of E60 covers both developing standards for E60 and supporting other ASTM committees in their development of sustainability-related standards.

ASTM Subcommittee E60.13 on Sustainable Manufacturing provides manufacturers with standards to assess and improve their processes and understand the implications of changes in the operation of those processes, specifically supporting methods and tools to assess and describe sustainability of manufacturing processes. These standards do not focus on any one process but rather provide guidance for implementing a continuous improvement process to reduce environmental impacts during the manufacturing phase of the life cycle. For a given manufacturer, understanding their processes is critical to improving their performance and to including sustainability goals in their decision making. The standards are broad enough that manufacturers can use them across multiple industries and for multiple applications. E3012, the Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes, helps manufacturers digitize their systems to better measure for environmental indicators. The subcommittee also provides guidance on investment analysis for introducing new technologies towards environmentally sustainable manufacturing. **Table 5** summarizes the current standards from E60.13.

Like ISO, other ASTM committees have developed or are currently developing standards that relate to CE and may be technology-, material-, or sector-specific. ASTM E60 has produced a database of sustainability-related standards, which is continuing to grow and will contribute to the numerous aspects of sustainability that will be necessary for creating a CE (ASTM International 2022b).

Standard Title	Description
E2979: Standard Classification for Discarded Materials from Manufacturing Facilities and Associated Support Facilities	Provides a system based on classification, location, disposition, and treatment of discarded materials for sustainability accounting purposes and key performance indicators (ASTM International 2022d)
E2986: Standard Guide for Evaluation of Environmental Aspects of Sustainability of Manufacturing Processes	Provides guidance to develop manufacturer-specific procedures for evaluating the environmental sustainability performance of manufacturing processes (ASTM International 2022e)
E2987/E2987M-20 Standard Terminology for Sustainable Manufacturing	Includes terminology applicable to sustainable manufacturing (ASTM International 2022f)
E3012: Standard Guide for Characterizing Environmental Aspects of Manufacturing Processes	Provides an approach to characterize any category of manufacturing process and to systematically capture and describe relevant environmental information (ASTM International 2022e)
E3096: Standard Guide for Definition, Selection, and Organization of Key Performance Indicators for Environmental Aspects of Manufacturing Processes	Provides a procedure for identifying candidate Key Performance Indicators (KPIs) from new and existing sources or new for environmental aspects of manufacturing processes (ASTM International 2018)
E3200: Standard Guide for Investment Analysis in Environmentally Sustainable Manufacturing	Guide for investors to make investment decisions for manufacturers based on their sustainable manufacturing practices (ASTM International 2021)

Table 5 Existing ASTM E60.13 Standards (2022)

2.5.4 **Reporting Standards**

According to the accounting firm KPMG, 80 % of the 5,200 companies they surveyed (representing the top 100 companies by revenue in 52 countries/jurisdictions) around the world (and 96 % of the world's 250 largest companies) published a sustainability report in 2020 (KPMG IMPACT 2020). Regulations and pressure from investors are both driving the creation of these reports and pushing companies to make their reports easy to compare. Reporting organizations promote interoperability among sustainability reports by creating standards for assessing and reporting on environmental impacts and progress towards sustainability goals. ASTM International Subcommittee E50 on Environmental Assessment, Risk Management and Corrective Action, has developed several reporting standards including: *ASTM E2173-22 Standard Guide for Disclosure of Environmental Liabilities*, *ASTM E3228-19 Standard Guide for Environmental Knowledge Management* (for documenting environmental risks), and *ASTM E2718-21 Standard Guide for Financial Disclosures Attributed to Climate Change*. Other international reporting standards organizations include the Sustainable Accounting Standards Board (SASB) that provides sustainability standards for 77 industries across 11 sectors, and the Global Reporting Initiative (GRI) that was used by two-thirds of the companies that KPMG surveyed (KPMG IMPACT 2020).

2.5.5 **CE Standards Gaps**

While significant efforts are taking place to develop standards in support of a CE, many challenges and gaps remain which can be improved by the strategic development of additional standards. Figure 6 depicts Milliken's version of the Zero Waste Hierarchy, adapted in part from the European Commission's Waste Framework Directive, prioritizing materials management methods as shown in proportion to their impact in reducing waste. Efforts should focus on the upper levels of the triangle, prioritizing, in order, redesign, reduction, and reuse above recycling, waste-to-energy, and disposal. In line with calls for a holistic view of a CE (see Section 1.4), all efforts to improve individual segments of the system should also consider how those efforts improve the system as a whole.

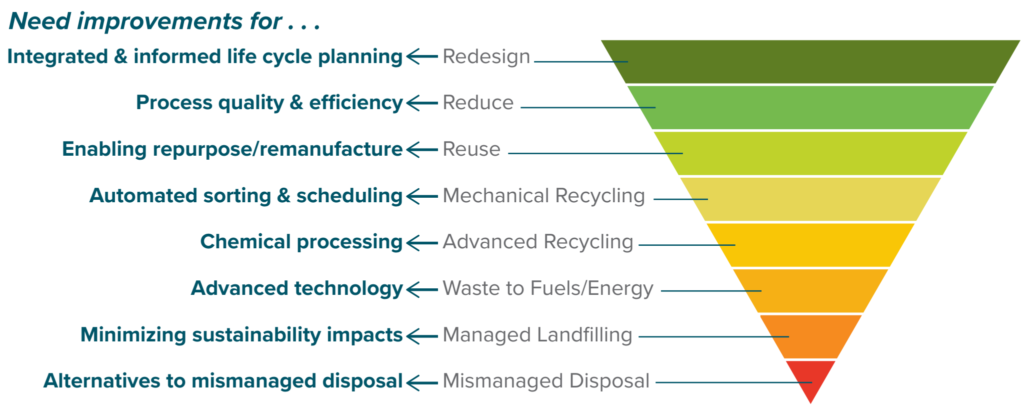


Figure 6 Zero Waste Hierarchy depicting necessary improvements and the need for standards (Billiet and Trenor 2020; Morris 2022)

Additional standards to support the CE will build on those already developed and will span product life cycle stages, supply chains, and industries. Future standards will be for optimizing systems, enabling circular design, improving operational efficiency of production, circulating by-product and otherwise discarded materials within manufacturing ecosystems, advancing mechanical as well as chemical recycling practices, and expanding the use of recycled materials into new products. More specifically, standards are needed to support the following:

- Enabling informed design and decision making, using information from across the life cycle
- Reducing discarded material flows
- Making discarded material flows more predictable in quantity and quality, and improving utilization
- Establishing baselines for measuring manufacturing process impacts
- Continuously improving by reducing resource use and establishing key performance indicators (KPI) that support sustainability
- Pursuing means of generating custom Life Cycle Inventory (LCI) datasets
- Providing guidance for manufacturers to for classifying discarded materials
- Fostering manufacturing marketplaces and systems to enable the reuse of material discards
- Identifying the most efficient circularity flows for material reuse

The remainder of this report identifies opportunities to promote manufacturing in a CE that were identified through the feedback and discussions during the Manufacturing Circular Economy Survey and the “Fostering a Circular Economy of Manufacturing Materials” workshop. That information was used to identify standards needs that ASTM Subcommittee E60.13 may consider when creating a roadmap of future work. This report and the standards needed will be informative not only for E60.13, but also for other ASTM committees, ISO (including ISO/TC 323 on Circular Economy), and other international and domestic standards organizations. Finally, this report and the next steps that it outlines provide actionable information and resources for researchers and those in the manufacturing sector interested in CE.

3 Survey: Manufacturing in a Circular Economy

In preparation for the workshop, ASTM Subcommittee E60.13 conducted a survey to learn what manufacturers are currently doing to improve sustainability, circularity, and to better manage materials. The survey was executed through SurveyMonkey and distributed through other ASTM committees, affiliate manufacturing networks, and via a social media campaign. The survey structure included 33 questions aimed at understanding (A) organization information (size, location, sector); (B) current sustainability/circularity initiatives such as efforts to reduce, reuse, and recycle materials; and (C) sustainability/CE-related goals, metrics, and current use of associated standards. A full list of the survey questions and responses is provided in Appendix A. In total, 259 respondents completed all or part of the survey. They represented organizations with manufacturing operations across the globe (**Figure 7a**) and of various sizes (**Figure 7b**).

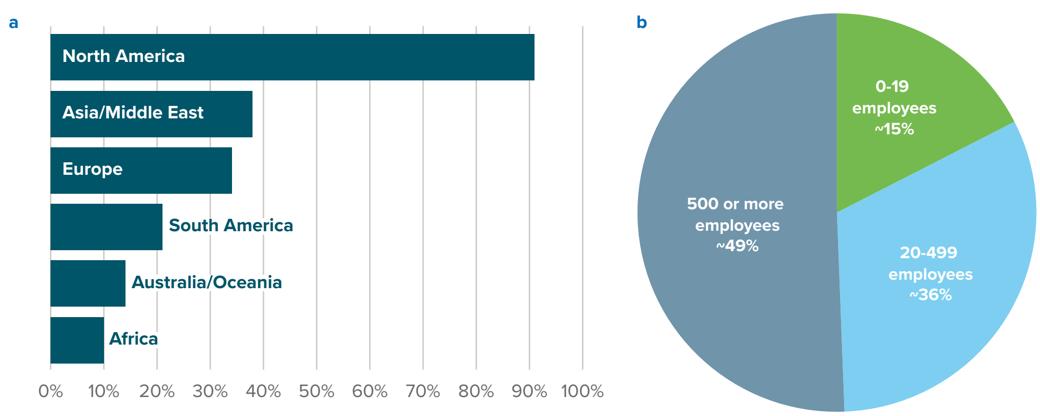


Figure 7
a) Regions in which respondents have manufacturing operations. b) Size of respondents' organizations

Most survey respondents noted manufacturing operations take place in North America—likely the result of the survey distribution leaning heavily towards U.S. companies. Additionally, respondents covered a wide range of sectors and professions including manufacturers, consultants, researchers, and industry groups. **Figure 8** depicts the breakdown of respondent representation, where the categories represent general manufacturing subsectors guided by the North American Industry Classification System (NAICS) (Bureau of Labor Statistics 2020).

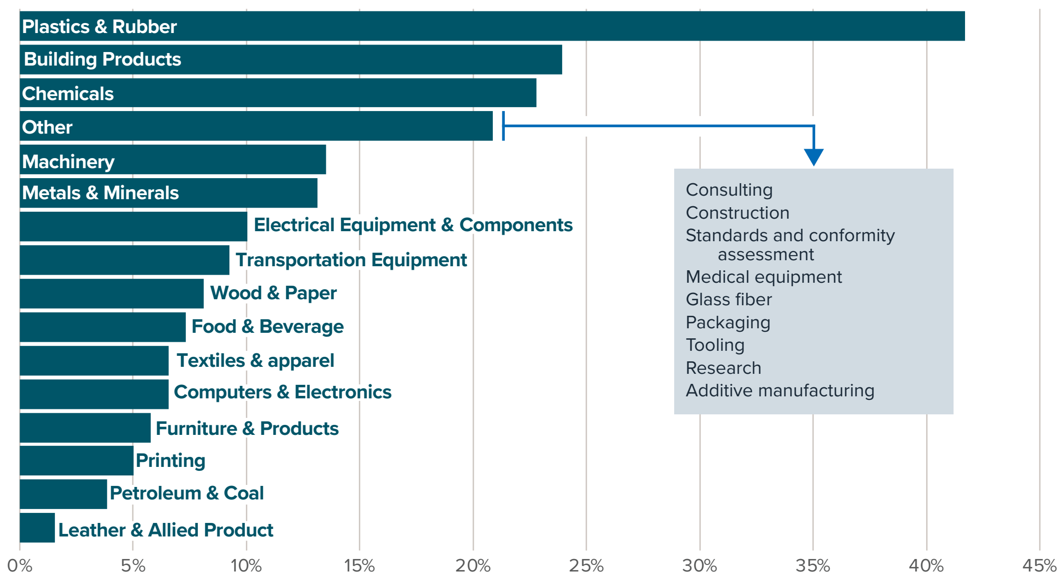


Figure 8 Industry representation in survey. Respondents often represent multiple sectors and thus values exceed 100% (n=259)

A series of Yes/No questions were asked to understand how respondent organizations address sustainability and circularity in their business practices (**Figure 9**). Respondents were also allowed to elaborate on their answers with a text box. The questions covered sustainability generally and specific circularity themes (i.e., waste reduction, reuse and recycling, and circular design). The first four high level questions are applicable across an organization, from the shop floor to C-suite and across supply chains. The final question addresses product design and thus may have a narrower scope of respondents, since small manufacturers in a supply chain are less likely to have control over the product design phase than an original equipment manufacturer (OEM).

Figure 9 Percentage of survey respondents regarding sustainability goals and targets (n=174-211)

Over 60% of respondents represent organizations with specific sustainability goals, but many fewer (35%) represent organizations with specific circularity or waste reduction goals. Almost half intentionally design for circularity (47%) or have specific diversion goals (46%), but fewer had ways of measuring how much waste they were diverting to recycling (40%). That said, it should be noted that the question specified diversion to recycling, but diversion may also include reduction, reuse, and composting (Environmental Protection Agency 2021). Respondents who elaborated on their answers to the reduction and diversion goals questions emphasized waste reduction and zero waste targets. Audits were also addressed, with some specifying that progress towards their waste reduction target is audited by OEMs or independent auditors, while others mentioned certifications (e.g., from the Sustainable Green Printing Partnership (Sustainable Green Printing Partnership 2021)). Those who brought up CE goals were vague. The percentage of waste that respondents reported diverting to recycling varied widely from 2% to 100% and from vague ("more than 60%") to specific ("3.40%"), suggesting different measurement techniques. It was also noted that the diversion rates differ based on the material assessed and facility.

Several themes emerged in responses to the product design question. First, respondents emphasized material type in the design phase; some mentioned integrating easy to recycle materials (e.g., metals like aluminum and steel), already recycled materials, and low-carbon materials (e.g., plant-based material like wood). Another theme of the responses was designing to extend the product's lifespan with techniques such as designing for longevity and serviceability/repairability. Design for Environment, Design for Recyclability, and Design for Disassembly were also mentioned several times.

Respondents also brought up challenges to implementing circularity in their processes. For example, "windows and doors are engineered to withstand extremes, meaning they are not readily disassembled. If they were, then they would not meet increasingly strict design and environmental guidelines. There is a juggling act between designing for the environment/disassembly and designing for an everlasting, outstanding product that will not need replacing in 5 years."

Circular manufacturing also entails improving process efficiency and reducing the generation of manufacturing waste. Various processes can support this effort, including reusing production by-products in-house, selling by-products to the market such as through secondary material marketplaces, providing to partner organizations (e.g., industrial symbiosis), or sending by-product materials for recycling. Survey respondents were asked which of these practices they perform with by-product material from their primary production processes (**Figure 10**). Respondents could choose multiple answers, so the total value exceeds 100%.

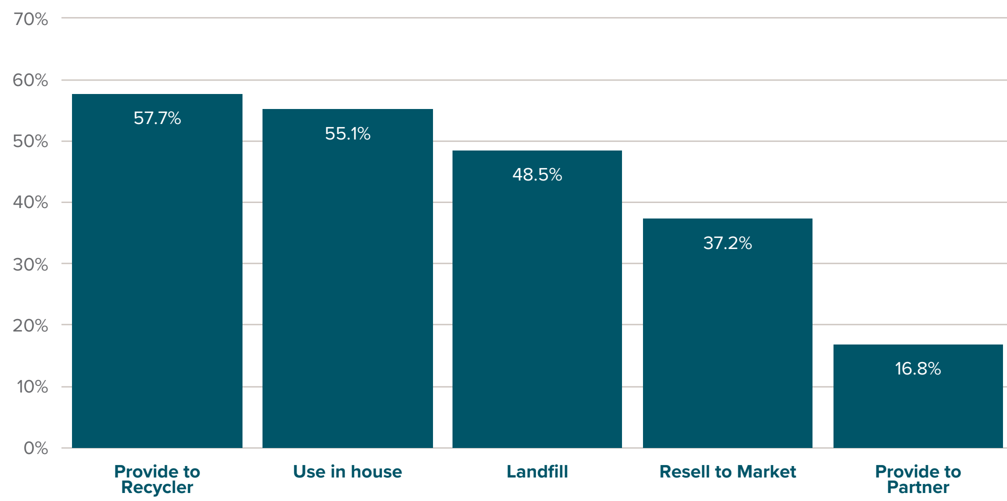


Figure 10 Percent of survey responses regarding what respondents do with by-products of primary production processes (n=196)

Most respondents reported sending by-products to recyclers (58%) or finding other uses for it in-house (55%). About half send by-products to the landfill (48%). Fewer respondents sell by-products to other organizations (37%) or provide by-products to partner organizations. Typically, sending material for recycling or to the landfill (or incineration) comes at a cost to manufacturers, and therefore these practices fail to recapture any value from the by-products. Alternatively, finding other uses for the materials in-house, selling them to secondary markets, or providing them to a partner recoups some level of value. One strategy for increasing a manufacturer's bottom line is designing processes that make by-products reusable; another strategy is making investments in robust secondary marketplaces (e.g., the U.S. Business Council for Sustainable Development's Material Marketplace, US Business Council for Sustainable Development 2022) and infrastructure to support industrial symbiosis.

The survey also included questions around circular manufacturing practices including drivers and barriers facing implementation (Appendix A). Responses to these questions are elaborated on in Section 4 in relation to drivers and barriers identified by workshop speakers and participants. The drivers and barriers questions were especially relevant to the workshop because they inform the goal of the workshop and this subsequent report to identify standards needs for the CE.

4 Workshop Overview

This section describes the "*Fostering a Circular Economy of Manufacturing Materials*" workshop, highlighting the objectives, speakers, participants, and organization. Session descriptions are also provided, including an overview of panel discussions and key takeaways. The workshop agenda and presenter lists are provided in Appendices B and C, respectively and Appendix D includes a brief overview of speaker presentations.

The workshop convened a wide variety of stakeholders, with a goal of better understanding ways that manufacturers can reduce waste in their operations and effectively keep manufacturing by-products and discards cycling within the economy. Participants represented standards bodies, brand owners, manufacturers from a broad range of sectors, the mechanical and chemical recycling industries, third party certification bodies, national laboratories, and industry associations. The desired output of the workshop was the identification of needed standards relevant to (A) manufacturing process improvements to track and minimize waste production, and (B) the development of a marketplace for discarded materials/by-products to stimulate material reuse including recycling. In addition, the workshop aimed to identify types of standards that ASTM International may prioritize (Committee E60 and beyond), as well as to compile a list of contributors for standards development.

Workshop planning and organization involved stakeholder outreach to identify core focus areas. The resulting agenda included two plenary presentations, four topic-specific sessions, and four round-table discussion sessions. Each topical session, described below, included a series of presentations by three experts followed by question-and-answers periods. The plenary presenters included KC Morris and Nabil Naser. KC Morris, co-chair of the E60.13 subcommittee and an expert in smart and sustainable manufacturing at NIST, provided an overview of manufacturing in a CE and the role of standards. Nabil Nasr, CEO of the REMADE Institute and expert in the field of sustainable manufacturing and remanufacturing, spoke about accelerating the transition to a CE. In total, the workshop brought together approximately 115 participants over 2 days.

4.1 Session 1: Foundations of an Industrial Circular Economy

The first panel session focused on the motivation behind and the foundations for a CE within the manufacturing sector, as well as existing standards that may be built upon. As previously mentioned, the CE paradigm considers a holistic view of product creation, use, and ultimately disposal in the context of the environment, the economy, and society. Consequently, characterizing each stage of a product's life cycle in terms of materials and information flows can help manufacturers better anticipate overall impacts of their products and processes (Reslan et al. 2022). The challenge of unifying, collecting and quantifying such data is one of several barriers to the development of better decision-making tools and metrics. The lack of data also hinders manufacturers' ability to plan their long-term sustainability initiatives (Wilts and Berg 2018).

This panel highlighted the need for better data in some key areas on which to build out sustainability assessment practices. In particular, the series of standards supporting Life Cycle Assessment (LCA) [ISO 14000 series] relies on Life Cycle Inventory (LCI) data for estimating product impacts. Such data can be used to inform future product designs, however, more such data is sorely needed to address the needs of CE. Needs exist for a broader range of materials data, more specific estimates of the impacts of manufacturing and recycling processes, and a greater understanding of how to account for new regenerative materials.

The speakers collectively highlighted the lack of a systems-wide approach for implementing CE practices. The current, mostly bottom-up approach has led to the creation of discrete environmental management and measurement standards. These typically address just one or perhaps only a few facets of CE. A single set of recognized global CE standards that unifies the different building blocks of sustainability practices and provides a basis to holistically quantify the overall degree of CE of a product or system is lacking. The new standards under development within ISO/

TC 323 on Circular economy aim to provide a platform to bring existing efforts into a broader CE framework, but the work is still nascent with the initial set of standards not anticipated until 2023. The speakers highlighted needs for real world case studies to validate new practices and proposed standards as they emerge.

The need for inclusivity was a key takeaway from this session. For instance, CE standards that are formulated must be flexible to accommodate not just different product families, but also large and small enterprises across both the developed and developing world. In addition, we need to have better material quality standards and a greater emphasis on standards that improve the overall degree of material recovery. This would encourage the creation of secondary industrial feedstocks and subsequently secondary markets. Further, information feedback loops at the EoL stage could enhance Design for Circularity (DfC).

4.2 Session 2: Recycling Today and Tomorrow

Speakers in this session discussed the current state of recycling practices among manufacturers and how they can be improved to respond to the circular economy. The panel highlighted the role of recycling in today's economy, how it impacts companies, and discussed in-house recycling efforts. The objective of this panel was to describe successful uses of recycled materials in manufacturing and the surrounding standards needed to better support these efforts now and in the future. Industry participants shared stories and strategies on how using such methods improved their company and furthered their goals of increasing circularity.

Key takeaways from the session suggest that there is *no one size fits all* in circular economy: different materials, products, and localities require unique approaches. Most industries would benefit from improvements to sorting and recycling. Also, consumer education is critical to facilitating a circular economy in the future. Panelists called for standardization efforts to reduce or even eliminate the co-mingling of plastics, to promote the use of plastics most likely to be collected and mechanically recycled, and to improve access to recycling and education around what can and cannot be recycled. Moreover, as we live in an increasingly interconnected world, identification standards are also needed.

4.3 Session 3: Circular Materials Management

With the ever-increasing growth of the global population and its needs, the earth's resources will not sustain current human consumption levels without better management of materials (Oberle et al. 2019; Branderhorst 2020). Therefore, more efficient material flows in which the resources are kept in use at a higher utilization level and over multiple use cycles (i.e., circular flows) are needed. Recovery processes such as remanufacturing, refurbishment, repair, and direct reuse are needed to enable higher utilization levels of material, in addition to conventional recycling (IRP 2018). This session focused on the available approaches to effectively manage materials used in manufacturing and identify avenues to minimize challenges to integrating recovered materials into a CE.

Several challenges and key takeaways were identified in this session. Beginning with the design stage, careful consideration of material choices and their utilization over the product life cycle is necessary to ensure circular materials management. Second, a CE has the potential to not only improve resource use and environmental and social sustainability but also increase gross domestic product (GDP), improving economic growth. Third, when quantifying avoided carbon emissions and other environmental impacts of repurposed materials (e.g., through a secondary materials marketplace), selecting a a scientific and consensus-based system of metrics to identify and allocate avoided carbon emission and other environmental impacts will incentivize participation in markets for secondary materials. Fourth, current CE efforts focused on vinyl material has confirmed the critical necessity of material characterization standards to improve the usability of material with recycled content. This is especially true with post-consumer recycling since it has more potential for contamination. Fifth, the current regulatory framework in the U.S. has resulted in a fragmented waste management system. Current regulations also do not explicitly define recycling, leading to confusion across the recycling and waste management industries. Therefore, consistent regulations would enable more uniform regional recycling infrastructure and practices necessary to achieve greater scale for economical post-consumer material recycling. Finally, better information flows (and information infrastructure) are necessary between the stakeholders to establish a CE. Even when there is demand for recovered materials, difficulties in locating suppliers and/or the lack of clear material characterization standards can inhibit effective circular material management.

4.4 Session 4: Designing Out Waste

This session aimed to introduce a design perspective for the adoption of the CE in the manufacturing sector. Product design represents the first bastion for consideration of the CE for a product life cycle. Products in a CE must be designed with the deliberate consideration that the product itself is the connective tissue between CE systems. These products must be adapted for life cycle systems that help recovery processes and increase recovery rates at EoL. As such, the CE introduces additional variables and uncertainty in an already complex product design environment. Today, designers need to be well equipped with tools that help improve life cycle data informatics, alleviate supply chain disruptions, decrease reliance on virgin materials, and facilitate an understanding of how design decisions impact product circularity. This session therefore covered how designers can consider CE principles in design, the role of design for disassembly in product circularity, and design tools and software applications that can aid in design for circularity.

Speakers in this session covered a wide range of topics, from product design platforms to buildings, in a CE. The commonalities of the three presentations are reflected in the future steps needed to realize CE design platforms, CE recycling programs, and CE certifications. All these initiatives are greatly enabled through the creation of standards and CE metrics. Moving forward, we should look to identify sector specific metrics that are key indicators of measuring the adherence to the proposed CE principles. These metrics and measurement methods could be standardized through standards groups like ASTM's E60. Furthermore, E60 can provide stewardship between sector-specific standard committees and their path toward drafting CE standards by serving as a center point for establishing common approaches to standardization.

5 Drivers and Barriers for Circularity in Manufacturing

Information gathered from survey responses, workshop presentations, and workshop breakout discussion sessions were compiled to identify key outcomes and common themes. This section presents those outcomes, describing identified drivers and barriers to circularity. Standards are built on industry consensus, so it is important to understand what is motivating (driving) as well as inhibiting the adoption of circular practices. Both the survey and workshop included diverse representation from across the manufacturing sector, enabling the identification of common barriers as well as the role for general versus targeted (e.g., sector or material specific) standards. By focusing on commonly agreed upon drivers and barriers, it will be possible to identify an initial set of consensus standards, thereby jumpstarting efforts in accelerating a circular economy.

5.1 Drivers for Circularity

Survey respondents were asked to select drivers that motivate the implementation of sustainable practices in their organization. A selection of drivers was provided based on literature review and expert insight, and respondents were invited to add additional drivers. Figure 11 depicts the resulting key drivers identified by survey respondents, organized by the percentage of responses. Multiple drivers motivate organizations to implement sustainable practices, hence the percentages in the figure exceed 100%.

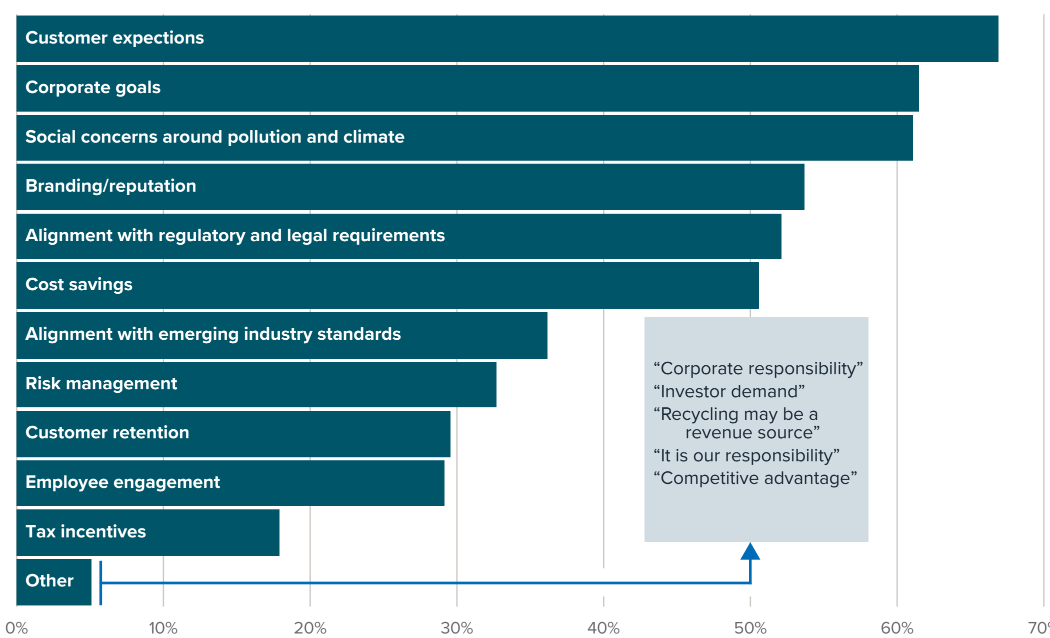


Figure 11 Motivators for implementing sustainable practices according to survey respondents (percent of responses) (n=257)

Drivers identified during the workshop closely aligned with those represented in **Figure 11**. Many represent organizational concerns that necessitate a top-down response from manufacturers to have the most impact. Based on the survey results and workshop discussion, key motivators for implementing sustainable practices can be generally categorized as follows:

- Customer demand
- Reporting and regulation
- Planning for the future

While overlap is apparent between these categories, drivers related to customer demand generally include customer expectations, social concerns around pollution and climate, branding/reputation, and customer retention. Customers are increasingly aware of environmental issues such as climate change and pollution and seek responsibly-sourced products and conscientious brands. This push from consumers is therefore influencing manufacturers to implement more sustainable production practices and make more circular products. This is exemplified by the survey responses, in which survey options related to customer demand accounted for three of the top drivers (selected by 50 % or more of respondents) (**Figure 11**).

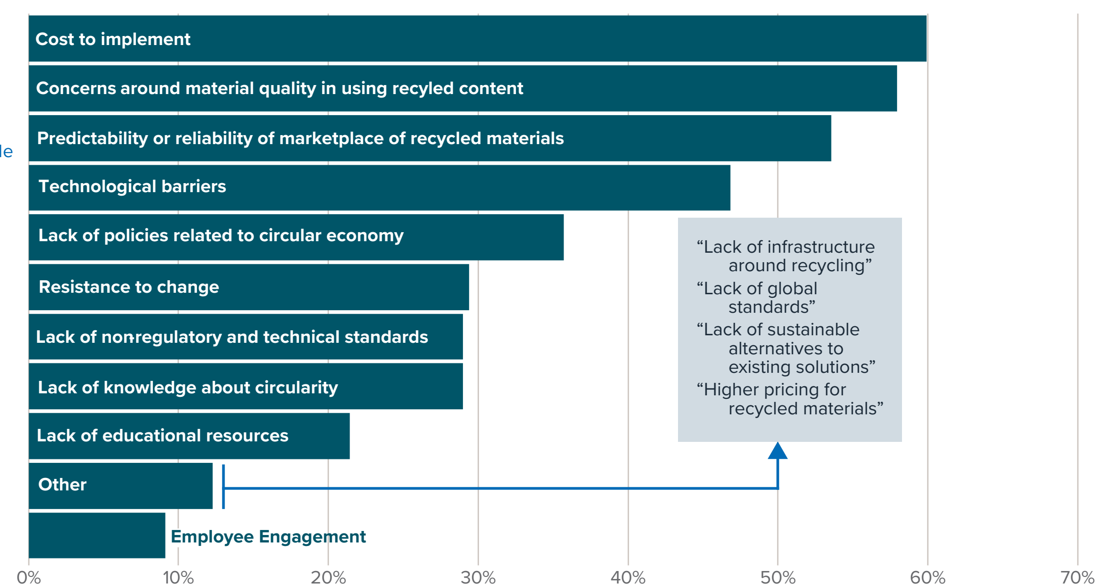
Reporting and regulation drivers include corporate goals, sustainability reporting, and alignment with both regulatory requirements and industry standards. Increasingly, manufacturers are establishing sustainability targets such as GHG emission reductions or recycled content targets, and documenting progress toward these goals in sustainability reports (see section 2.5.4). Additionally, U.S. states and the federal government are increasingly considering and/or passing laws aimed at improving the circularity of goods, including, for example, manufacturer responsibility for packaging (e.g.,Senator Michael Dembrow and Representative Janeen Sollman 2021; Cutter, Priola, and Gonzales 2022) and recycled content mandates (e.g., Stanford et al. 2022; Ting, Philip Y. 2020) . Aligning with emerging non-regulatory standards was also identified as a motivator for manufacturers to adopt more sustainable practices.

Drivers related to future planning include employee engagement, corporate goals, and social concerns. Employee engagement and retention was uniquely pointed out in the workshop as a driver, particularly for SMMs. The observation was that forward thinking and environmentally conscious companies will better attract and retain millennial-aged workers. While larger companies may have resources and corporate mandate for circularity, smaller organizations may be motivated to incorporate circularity and sustainability into their business model to attract and retain employees.

5.2 Barriers to Circularity

Survey respondents were also asked to select barriers that they face in implementing sustainable practices. A predetermined list was provided based on literature review and author insights, but respondents were also invited to add additional barriers. Figure 12 provides the resulting key barriers based on the percentage of responses as well as a selection of additional barriers stated in the comments. Like drivers, organizations face multiple barriers and therefore the percentages in the figure exceed 100%.

Figure 12 Barriers to implementing more sustainable practices (percent of responses) (n=252)



Survey respondents identified several concerns that inhibit the uptake and implementation of sustainable practices. Foremost are concerns about financial aspects and the quality of materials containing recycled content. Additionally, respondents ranked the lack of predictability and reliability of recycled materials in the marketplace as barriers to circularity. Infrastructural barriers, including technological challenges, were further noted as inhibiting more sustainable practices. Workshop speakers and participants echoed these concerns. The following discussion dives deeper into these barriers as well as others discussed by participants in the workshop.

5.2.1 **Financial Concerns**

Both survey respondents and workshop participants noted financial concerns as a key barrier to the implementation of more circular and sustainable practices. These concerns stem from the financial feasibility of adapting manufacturing systems and practices to be more sustainable and unknowns pertaining to the resulting return on investment. Many manufacturers assume that investing in, for example, pollution prevention, energy and material efficient practices, and waste management do not return the upfront costs within the desired time frame. As such, a common fear exists that sustainable manufacturing will be costly and that sustainably produced products will, therefore, be more expensive.

Additionally, many recycled materials are currently more expensive than their virgin counterparts. Recycled polymers, for example, tend to be more expensive than virgin fossil-based polymers, a result of the extensive processes associated with collecting, sorting, cleaning, and recycling of polymers back into feedstock form. Virgin polymers, on the other hand, are derived from well-established processes operating at economies of scale not yet seen in the recycling industry. This additional cost of recycled-content feedstock, together with the unknown properties associated with recycled materials (discussed in Section 4.2.3), is a significant barrier preventing manufacturers from opting for recycled material inputs.

Manufacturing in a CE also requires manufacturers to adapt business models not only to produce more sustainably today, but to consider how products will be used and processed in the future. For example, many EPR laws put the responsibility for EoL management on manufacturers, often requiring them to take products back for recycling. Depending on the product, EoL activities may not be necessary for years or decades following the time of production. Expanding the scope of business to include how products are used or managed in the future is a significant challenge for manufacturers and necessitates additional attention and resources that may not be included in the current business model.

Many manufacturing companies have well-established operations and supply chains and, therefore, the very idea of changing their way of doing business is a hurdle. This pertains not only to the economic side of implementing circularity, but also to the infrastructural dimension. Workshop participants noted that this is a barrier for the plastics and chemicals industry in particular, where supply chains and production infrastructure are rooted in the petrochemical systems in existence since the mid-twentieth century.

Liability concerns sway many manufactures away from utilizing recycled material inputs as well as partaking in reuse, repair, and remanufacturing endeavors. Concerns with the quality of recycled content is discussed in the next section, but manufacturer apprehensions about extending the life of products through reuse (resale), repair, and remanufacture typically stem from not having information about the prior history (use phase) of the product and, therefore, being unable to identify or verify the product’s remaining quality or useful life. Other liability concerns are sector specific, such reliability of reused or repaired medical equipment, contamination concerns of used mattresses or textiles, and structural durability of repurposed construction elements (e.g., bridge girders).

The concerns discussed above are particularly felt by SMMs, who may not have the financial capacity to upgrade equipment, adapt processes, change supply chains, or address liability issues in the name of circularity. For instance, SMMs may not have the financial capital necessary for upfront costs associated with transitioning to sustainable operations. Further, SMMs may not have the capability to extend their business model to take products back for repair or reuse years after production.

5.2.2 **Material Variability and Quality**

Survey respondents and workshop participants also identified the quality of recycled materials as a key barrier to implementing sustainable practices. An important component of circular manufacturing is the utilization of recycled material feedstocks in production processes. However, both pre- and post-consumer materials sent for recycling vary greatly in terms of material composition, quantity, and quality. This multi-faceted challenge includes issues associated with collection, sortation, and recycling processes and infrastructure as well as low tolerance requirements for contamination or impurities in feedstock streams.

While many manufacturers are incorporating secondary materials streams into the manufacturing processes, the breadth of his practice is often hampered by inconsistency of the recycled material streams. The number and combinations of materials used in products and packaging continues to increase and recycling sortation and separation processes are incapable of isolating each category. As such, recycled materials for use in the manufacture of new products are rarely pure, and in many cases, accurate identification of all materials and contaminants therein is not possible.

Mixed or contaminated material streams can be detrimental to manufacturing processes, potentially increase the risk associated with products or operations, or result in inferior products. Some sectors require material inputs to have a clean chemistry, i.e., free of any impurities or contamination to a high degree (e.g., 100 ppm or less), while others have a red list of ingredients not permitted in their operations. Achieving these high purity requirements with recycled content is a challenge as it is difficult to guarantee the type and degree of contaminants in pre- and post-consumer waste streams. For example, food and medical-grade packaging have stringent purity requirements that are difficult to meet with recycled content. A further complication is the potential for the future awareness and recognition of contaminants not considered today. Certain flame retardants, for example, were only recently recognized as harmful despite their use in many consumer and industrial products to decrease ignition since the 1970s (National Institute of Environmental Health Science 2021). Similarly, additives that are acceptable today, such as those used to promote performance characteristics, may no longer be so in 10 to 20 years.

The Case of Plastics

Plastics manufacturers are increasingly asked to increase their use of recycled polymers in the production of new plastics. Currently, recycling of plastics is limited, but typically includes PET (polyethylene terephthalate), HDPE (high-density polyethylene), and in some places PP (polypropylene). These are collected, aggregated, and then sorted by resin type for reprocessing back into their respective resin types in the form of pellets or flakes. But sorting and separating by resin type is imperfect and polymer blending occurs in recycled streams. This blending of polymers makes it very difficult to monitor performance in reprocessing operations (e.g. extrusion), especially when the blend continuously changes due to fluctuations in the recycling stream. There are many safety factors built into the production and use of plastics, resulting in low tolerance requirements for impurities. Whereas virgin polymers have established specifications, recycled polymer streams currently have no such impurity specifications.

While virgin feedstocks typically have specifications with required material or performance properties, such specifications do not yet exist for recycled materials. Hence, supply chains, production systems, and even product designs rely on the established materials and procedures in place that are consistent and standardized. The short history and variability of recycled content does not yet offer manufacturers the same reliability or confidence. Thus, the challenge remains as to how to integrate recycled materials so that engineers and designers can use them reliably. Manufacturing designers need an exact understanding of their production inputs, which is difficult to obtain from recycled materials. Specifications may help address this challenge; however, workshop participants fear that understanding and developing the material quality specifications needed for production with recycled content may necessitate proprietary information or rely on trade secrets, limiting the sharing of vital information.

Another challenge facing the uptake of recycled content feedstocks is the inability to trace recycled materials through the production system. Manufacturers want to market the inclusion of recycled materials in products; however, recycled metals, polymers, and pulp, for example, are indistinguishable from their virgin counterparts and no method exists to track those materials into the final product. Therefore, it is difficult for manufacturers to make verifiable recycled content claims on products. Chain of custody (CoC) approaches (e.g., Mass Balance Accounting) have been developed to account for recycled content in products but currently no standards exist to uniformly validate recycled content claims (Beers et al. 2022).

5.2.3 **Reliability of Markets**

The lack of predictability and reliability of the marketplace for recycled materials is also a barrier to circularity according to both survey respondents and workshop participants. Like their need for consistent material quality, manufacturers also need a constant, consistent supply of recycled materials to create products with recycled content, something the current recycling market cannot yet guarantee. The volume and composition of the recycling stream change temporally as products and trends pass through life cycles as well as geographically as regions collect different materials and forms factors for recycling. Such variability means that producers cannot rely on incoming material flow rates or qualities.

A tangential challenge here is that a material may take a different form at its EoL than when it was put on the market. For instance, a manufacturer that uses paper to produce toilet paper knows that at its EoL, toilet paper creates a new (and different) waste stream as sludge. Similarly in the plastic industry, a resin such as PP does not return to a manufacturer after use and recycling as the same material because the monomers have changed. It is therefore important that waste streams do not become another linear stream, but rather efforts are made to make materials that are available into opportunities.

An additional market-based challenge revolves around less commonly recycled materials and materials that face more difficulty fitting into the CE. Wood is an example, which despite its extensive utilization, does not have strong reputation for circularity at scale. Wood is often incorporated into products as one of multiple materials (e.g., furniture), and is often treated with paints, varnishes, or other chemical substances. Hence, wood mills are resistant to taking back and reclaiming used wood because, according to workshop participants, doing so would require not only a transition in product design but also in the production system. Hence, finding circular outlets for these waste streams remains a challenge.

5.2.4 Infrastructure Challenges

Technological and infrastructural barriers were also identified as a challenge, with the need for an efficient and profitable recycling infrastructure specifically mentioned in the survey comments. One survey respondent noted "the technology exists—it simply has not proved profitable. Until recycling becomes a revenue source, rather than a cost; sustainable practices/recycling will not be accessible to many smaller-to-medium size businesses." The current U.S. recycling infrastructure was considered inefficient by survey and workshop participants, in part because of limited sorting capabilities and low recycling yields. This is in part the result of federal legislation not clearly distinguishing recycling from waste management, which workshop participants believe has led to the current infrastructure problem. Legislative definitions of "discard" are argued to have direct relevance to whether and how materials flow through circular pathways (reuse, recycling). The geo-specific nature of recycling is also a hindrance, as materials and volumes collected for recycling are regionally dependent. So long as recycling infrastructure is unique and distributed geographically, costs will be at the mercy of local markets which may be prohibitive for organizations, particularly SMMs.

Conditions Favorable for Recycling

—David Wagger, ISRI

1. Sufficient material value
2. Sufficient material available for recycling
3. Cost-effective recycling technology(ies)
4. Efficient material logistics
5. Markets for recycled material
6. Favorable policies, laws, and regulations

But improving the efficiency, and thus reducing the cost of current recycling processes is also challenged by the increasing complexity of materials, products, and packaging entering the recycling system. Plastics provide an example here, where new polymer formulations, additives, and form factors are continually introduced into the marketplace, which then often requires new infrastructure to process. Recyclers are also grappling with the particular challenge of dealing with post-consumer materials which have varying properties and may contain different types and degrees of contamination and unique process additives..

Advancements are being made in recycling technologies, particularly in the development of chemical recycling processes to recover polymers. Traditionally, polymers have been mechanically recycled, in which recycled polymers are melted and reprocessed back into flakes or pellets without modifying the underlying polymer structure. However, the existing mechanical recycling infrastructure is limited in its ability to recover all types of plastic waste, to supply the quality and quantity of recycled material needed to meet functional requirements, and to meet the purity requirements needed for food packaging, medical-grade applications, and transparent materials (e.g., automotive headlamp lenses). As a result, chemical recycling – which reduces recycled polymers to their original monomer form or other small molecule precursors for reintroduction into the supply chain – has great appeal, especially for the polymeric products, which remain challenging to recycle mechanically. Significant efforts are taking place to scale up chemical recycling infrastructure, but further work is needed to understand the environmental impacts of the processes (e.g., energy demand/GHG emissions). Also, it is important to identify where chemical recycling can be useful in relation to mechanical recycling so as not to compete for materials or markets.

Another infrastructure challenge pertains to safety in the processing of the increasing number of hazardous (or potentially hazardous) materials that reach EoL. As indicated previously, many products put on the market contain chemical substances such as brominated flame retardants, paints, water-resistant sealants, and additives, to name just a few. Processing products with these chemicals poses a potential health and safety risk for recyclers and necessitates advanced recycling equipment. As an example, the current infrastructure to safely repair, recycle, or dispose of lithium-ion batteries is limited. These batteries are increasingly utilized in automobiles, electronics, and clothing and accessories, yet their presence in the waste and recycling streams poses a fire threat because they can easily ignite when damaged.

Just as the existing recycling infrastructure may not be capable of supporting circular manufacturing, manufacturing infrastructure is also not currently equipped to support circularity. A survey respondent noted this gap, identifying the "need for circular infrastructure, including take-back structure/business within the company or with other corporate partners." Manufacturing infrastructure is also not prepared to incorporate recycled materials into products. As indicated above, incorporating recycled inputs necessitates transitioning not only product design but also production systems and infrastructure. In the industrial system, manufacturers have individually invested millions of dollars in capital into equipment designed to process products efficiently, and thus switching to a new type of system often requires new investment at the same scale, with an unknown or higher return on investment.

5.2.5 **Information and Communication Gaps**

A key takeaway from the workshop was that the flow of information is critical to support circularity in manufacturing and communication across the supply chain and that product life cycles are integral to these flows. However, workshop participants pointed out that there are significant information and communication gaps inhibiting circularity. Data exchange, for example, is necessary to guide circular decision-making across the life cycle, yet useful and verifiable data are currently scarce due to proprietary restrictions and a weak data infrastructure to support the collection of and access to necessary data. For instance, workshop participants called out that the lack of a database of recycling facilities inhibits their ability to recycle more. Data to support circularity should be easy to find, accessible, interoperable, and reusable (FAIR), yet the necessary systems for harmonization, collation, and access to achieve these FAIR goals are lacking. Further, whereas data and information typically flow in the direction of the supply chain, information also needs to move counter-current in a CE. Only then do stakeholders have the information necessary to follow circular principles. For example, feedback from EoL recovery processes guide product designers as they incorporate DfC principles.

A communication and information exchange infrastructure that brings together and is accessible to the broad group of stakeholders of the CE is lacking. Stakeholders looking to expand their volumes or scope face difficulty finding material sources and collaborators. For example, one workshop participant who represents a PVC recycler noted his frustration with how difficult it is to connect with market players who want recycled PVC.

Additionally, it is difficult to communicate key information about products with a long lifespan that will allow them to re-enter the economy. Consider a building for example, where the components and materials will be in place for decades, if not centuries, and will often go through several owners and users as well as changing technology mediums. How, where, and who is responsible to keep information about those materials and updates is undecided, yet that information is necessary to recirculate the building's materials into the economy when that building is decommissioned. As such, the need for communication around products extends well into the future.

Communication to consumers and the public about CE and associated products is also proving to be challenging. Consumer awareness and buy-in is integral in the transition to a CE, yet widespread education campaigns about e.g., recycling services and what to recycle are thwarted by the fragmented system. Consumer education is also needed to raise awareness about purchase decisions and to support circular markets. However, brand owners take the risk of greenwashing accusations and reduced credibility if claims are not understandable and verifiable. Additionally, there appears to be a perception among consumers that repaired or remanufactured products are inferior to new products. To date, the repair and remanufacturing sector does not have a means to validate and convey the reliability, durability, and functionality of repaired/remanufactured products.

5.2.6 **Trade Barriers**

Workshop participants identified trade as another barrier inhibiting circularity, particularly the international trade of recycled materials and repaired or remanufactured products. International and national trade codes (tariff codes) are used to classify physical materials and products imported into and exported from the U.S. (See Appendix F for an explanation of trade codes, administrative bodies, and criteria for adding new codes). In most countries trade codes traditionally follow raw materials and finished products entering and leaving U.S. borders and therefore codes may not exist for recycled or repaired/remanufactured goods. Without these classifications, governments and businesses cannot collect data pertaining to the types and volumes of circular materials traded and thus cannot conduct important market analysis or monitor growth in trade. Further, this makes it difficult both for recyclers to sell recycled content and for manufacturers to purchase these goods on the international market. Efforts have been made to create new trade codes—for example, for recycled plastic resin—but they have been rejected on the basis that U.S. Customs and Border Protection (USCBP) cannot verify whether a product contains recycled content.

5.2.7 **Measurement and Modeling Challenges**

Metrics, measurement approaches, and modeling tools have yet to be agreed upon or harmonized across the CE, which impedes organizations' ability to implement, prioritize, and track the progress of circular practices. CE metrics are needed to support the business case for circularity, as well as to aid in circular decision-making. For instance, a CE calls for the pursuit of higher value recovery options (e.g., reuse, repair, remanufacturing) before recycling, but metrics and measurements are still needed to optimize decision-making from financial and sustainability perspectives. Without uniform metrics to quantify circularity, organizations can create their own measures which are then not consistent from one manufacturer to another, leading to confusion on the part of customers. Further, organizations are unable to benchmark progress and set measurable and comparable goals.

Modeling tools such as life cycle assessment (LCA) and material flow analysis (MFA) are expanding in scope and application, yet are challenged by lack of harmonization, limited data availability, and lack of transparency in calculations. LCA is used to model the environmental impacts associated with the life cycle of a material or product, whereas MFA aims to quantify flows and stocks of materials in a system (e.g., through an organization or the economy). Organizations use LCA tools to help them determine which processes, materials, and products pose or could mitigate negative environmental impacts. However, given that LCAs are primarily performed in-house or by third-party organizations and are based on propriety methods and data, they are often not transparent or repeatable. This makes comparisons across the industry difficult, if not impossible. Additionally, LCAs typically compare material options (e.g., wood versus concrete) or the efficiency of product designs. Further, the scope of the LCA may affect the reported outcomes. For example, an LCA that is scoped to a production rate of 100 may not be comparable with that of a product with a higher production rate.

5.2.8 **Limits to Circularity**

A final barrier identified through workshop discussions and survey responses is the ambiguity associated with the CE and the realization that circularity is limited. Fundamental questions pertaining to when we will know if a CE has been reached, if it can ever be fully achieved, or whether and to what degree a linear economy will still exist in a more circular future dampen the motivation to implement CE practices. Additionally, the mere fact that there are limits to circularity introduces skepticism. Some materials should not be maintained in the economy, such as those hazardous to human or environmental health. Other materials are dissipative by design (e.g., brake pads, galvanized steel) or inevitability (e.g., rubber tires), and therefore cannot be made completely circular. For some, the energy and resources needed for EoL recovery actually render circularity *un*sustainable (e.g., recovery of select precious metals used in electronics) until further technological advancements are made. We are constrained by the laws of physics, and thus there will always be losses in the system. And in some cases regulations and safety issues preclude circularity, such as the reuse of flooring that could contain asbestos. While these problems are daunting, recognizing them can be grounding and support a more realistic framework moving forward. By realizing the systemic limits of the CE and making those limits the targets of our efforts, we will make more rapid progress toward a *more* CE.

The ambiguity around circularity—what it means, how it is measured, and whether and under what conditions it can be achieved—motivates the need for consensus-based standards where multiple perspectives come together to address such topics and find a beneficial path forward to the betterment of all.

6 Standards Needed to Support Circular Manufacturing

Standards will play an important role in addressing the barriers identified above. This section outlines areas for standards development based on the survey results, workshop presentations, and expert discussions. They have been categorized into 1) foundational, 2) system support, 3) front-end design, 4) manufacturing production, 5) back-end recovery, and 6) recycling-related standards.

Some areas discussed below warrant the creation of "standards-for-standards". These are areas where one standard is insufficient or inappropriate to be applied across different material types or product streams. Rather, a standard can be developed that outlines the characteristics or components that a material/product-specific standard should include. Specific areas for these standards are discussed where appropriate in the sections that follow.

6.1 Foundational CE Standards

Standards are needed to support the foundational underpinnings of circular manufacturing. **Table 6** presents potential foundational standards, including agreed upon definitions for CE concepts, the establishment of which would allow manufacturers, circular providers (e.g., recovery processors), governments, and consumers to "speak the same language." A common language would also facilitate the exchange of data and other information

Focus	Description
Definitions/ terminology	– Terminology definitions to harmonize language – Methods for metric definition and selection – Terminology and methods for operationalizing the value hierarchy across the life cycle – Methods for carbon accounting calculations (saving/neutral/credits) to harmonize approaches and ensure no double counting
Corporate Benchmarking & Reporting	– Measurement methods for CE and ESG metrics to make benchmarking and reporting consistent, repeatable, and verifiable – Specifications for measurements for circular assessment – Guidelines for the development, use, and validation of models and tools for LCA, MFA, Techno-Economic Assessment (TEA), and integrated models – Guidance for assessing reduction in environmental impacts – CE and ESG reporting criteria
Life cycle Assessment & Inventories	– Guidelines for factoring decarbonization in LCA (e.g., light-weighting, extending lifetime, recapturing at EoL) – Guidance and test cases for LCA model harmonization and interoperability – Guidelines for adapting LCA for the CE – Guidance for LCI (Life Cycle Inventory) development – Test cases and datasets for LCA to benchmark for models/tools

Table 6 Foundational Standards for a CE

among stakeholders and across product life cycles. As of 2023, a working group of ISO/TC 323 is developing such terminology, and ASTM E60, as the U.S. TAG to ISO/TC 323, supports these efforts. Foundational standards will contribute appropriate metrics, measurements, and models to make circular benchmarking and reporting consistent, repeatable, and verifiable. Additionally, standards can be expanded upon to harmonize LCAs and improve compatibility and interoperability between studies. Specifications for LCA methodologies can promote repeatability of studies through transparency of data inputs and calculations. Such studies will help to guide users on how to account for decarbonization opportunities such as light-weighting (e.g., of vehicles or packaging), life extension, and recovery at EoL. Standards can similarly specify measurements of carbon consumption and reporting schemes to promote consistency and verifiability.

6.2 System Support

Closing the material flow loops across the life cycle of products and materials will require standards for practices and approaches across the value chain. **Table 7** outlines such standards, focusing on facilitating "systems thinking" and improving mechanisms to collect, channel, and administer information throughout the life cycle. Such mechanisms require information standards for traceability, digital threads, and advanced labeling. Traceability standards can provide stakeholders across the supply chain and product life cycle with a way to access historical data on products and the materials therein. This data can offer manufacturers confidence in the provenance of materials and components, provide consumers with the information necessary to judge the sustainability of goods for procurement and optimal use of the product, and determine the appropriate end-of-use circular action. Furthermore, traceability can support recovery decision-making by providing the information necessary to determine the optimal recovery path (e.g., repair, remanufacturing, or recycling) for the product.

Information on the history and composition of the product from its design, manufacturing, use, and disposition can all be documented by creating a digital record. Such a record could provide information on the product's material composition, wear and tear, functional performance-levels, guidance for repair and dismantling, and even ownership records. Standards are needed to designate the specific information to capture, which technologies to use, how to share it—with whom, up to what level of detail, and in what circumstances—and how to prevent unauthorized access.

Labeling provides a more accessible means to share information about a product with any stakeholder who encounters the product, including manufacturers, users, and downstream processors. Labeling standards can specify protocols for relabeling when products undergo significant recovery transformations and can help recyclers reduce contamination and material cross-over. Labeling standards can also be used to define how claims such as recycled content and recyclability are marketed to consumers in a more consistent manner.

Focus	Description
Systems thinking	– Facilitating systems-thinking for manufacturing circularity at material, product, and packaging levels (e.g., matching packaging recyclability labels with recycling infrastructure categorizations)
Traceability & Digital Records	– Material identification and traceability throughout the value chain (e.g., Chain of Custody) – Use of traceability to facilitate take-back/return business models – Universal product identification (e.g., barcodes, QR codes, RFID, blockchain, etc.) – Management of product life cycle information (collection, storage, availability, interoperability) – Adapting security standards for CE
Labeling	– Persistent identification of materials – Labeling of product's/package's recycled content level – Labeling of product's/package's recyclability – Material labeling on products and components

Table 7 System Support Standards

6.3 Front-End Design Standards

Designing for circularity (DfC) is the essential first step in tracking a product through a circular life cycle, as design decisions can determine the fate of product use, life extension opportunities, and disposition at EoL. The standards outlined in **Table 8** are needed to drive circular design of materials and products. They include general DfC guides to operationalize the zero-waste hierarchy (see Section 1.5.5) and develop circularity measurements for design evaluation and comparisons with alternative approaches. Designing a product involves balancing an array of tradeoffs and constraints from companies, consumers, and regulations, and DfC standards can guide designers to operate within those constraints while fostering a CE.

Focus	Description
Design for Circularity (general)	– Guidance for parameterizing and operationalizing circular design criteria – Guidance for measuring trade-offs in design – Circular Product Design Principles – Methods to normalize and assess circularity potential – Guidance for factoring in EoL in design decisions – Guidance for product circularity comparison – Guidance for operationalizing the value hierarchy in design: e.g., assessing and valuing reuse vs remanufacture vs recycling
Design for Material Circularity	– Material Hierarchy, Material Circularity Index matrix – Specifications for incorporating recycled content in products – Guidance for design materials that are safe for secondary use: e.g., satisfy regulatory requirements such as food contact – Guidance for agile design responsive to uncertain material stream
Product Design for Recovery	– Guidance for ease of product assembly/disassembly: e.g., possible with commonly available tools – Guidelines for remanufacturing – Guidance for ease of repair: e.g., accessibility to parts more likely to fail (batteries) – Guides for product geometries suitable for recycling: e.g. low complexity, reduced/eliminated co-mingling of materials – Guidance for measuring and verifying product durability

Table 8 Design Standards for a CE

Design for materials circularity entails identifying and developing materials that are best suited for a CE—i.e., they are non-hazardous, high-purity and quality, and recyclable. Standards to support materials design can thereby specify material properties, quality, and performance. Further, specifications can be developed for incorporating recycled content into the production of new materials. For example, standards can prescribe how to incorporate recycled cotton into the production of new textiles or recovered polypropylene from carpet into the production of engineering plastics.

Product design standards can specify how to make products that are built for durability, yet capable of disassembly and recovery, i.e., designed for circularity. These standards can prescribe assembly strategies that support disassembly for recovery as well as configurations and geometries best suited for recovery strategies. For example, electronics design standards can provide the optimal location of parts most likely to fail (e.g., batteries) for ease of repair as well as connection mechanisms for accessibility such as screws rather than adhesives. Design for recovery standards will also ensure that more recycled material is available for recovery. Currently, demand for products with recycled content is outpacing the supply of recycled material, and one way to balance this dynamic is to increase the availability of used material for recycling by designing products to recycle. In addition, design standards need to consider expected product lifespans as different standards may be required for short-life products (e.g., packaging) compared with those with long lifespans (e.g., buildings).

6.4 Manufacturing Production

Manufacturers have opportunities to reduce their own material use through better process efficiency, participation in secondary materials marketplaces, and improved supply chain management with a focus on sustainability and circularity. Table 9 highlights standards needed to facilitate production improvements in these areas. Process improvements aim to make operations more efficient in terms of resource use and waste reduction, as well as time and human capital. Standards in this area can help by providing guidance for measuring operational efficiency and performing waste audits. Manufacturers are striving to reduce the volume of material sent to landfill and are thus seeking alternative outlets for process by-products. Standard guides for developing and expanding secondary materials marketplaces, such as the U.S. Business Council for Sustainable Development's Materials Marketplace (US Business Council for Sustainable Development 2022) would help establish trust and participation in these markets.

Supply chain sustainability can be enhanced through standardized guides describing responsible sourcing protocols and implementation of traceability mechanisms to track materials through the supply chain. Further, guides are needed to outline how to measure and assess circularity and/or sustainability of supply chains including all scope emissions. Guides of this nature would enable benchmarking and measurable improvements across companies and industries.

Focus	Description
Supply Chain	– Guidance for selecting local and/or collocated suppliers—eco-industrial parks – Guidance for responsible sourcing: e.g., renewable, recycled, locality – Guidance for traceability of supply chain materials; e.g., digital transaction certificates to trace material through the supply chain – Guidance for assessing the circularity and/or sustainability of supply chain: e.g., Scope 3 emissions, material provenance
Process Improvements	– Specifications to measure environmental performance of manufacturing processes: e.g., climate emissions, water use – Guidance for assessing and measuring operational efficiency – Specifications for product digital twins for pre-production planning – Guidance to measuring waste and operationalize waste reduction – Guidance for performing waste audits
Secondary Materials Marketplaces	– Guidance for developing and operating material marketplaces – Metrics for quantifying environmental impact reductions due to marketplace transactions – Specifications for composition, quality, and quantity of manufacturing by-products (i.e., discards with re-use potential) – Metrics and guidelines for specifications for product reuse (e.g. remaining useful life, guidance for characterization of secondary materials) – Guidance on allocating the environmental impact reduction/avoidance of marketplace transactions, between stakeholders

Table 9 Manufacturing Standards for a CE

6.5 Back-End Recovery

Distribution, use, and reuse phases traditionally follow the transition of ownership from manufacturer to consumer and then to waste management. CE is inspiring other forms for ownership wherein producers take on longer-term responsibility of products including facilitating life-extension through repair, refurbishment, and remanufacturing. Table 10 lists several of the standards needed to foster these life-extension practices and ensure products remain in the economy at their highest value for as long as possible. The table includes general standards that support all recovery processes as well as standards specific to each recovery process (i.e., reuse, repurpose, repair, refurbish, and remanufacture). This is an area where "standards for standards" could be developed, in which a standard can specify the characteristics of product or more material-specific standards. For instance, a standard can be developed that specifies what guides for product and/or material collection should incorporate. They can further itemize the breadth of factors to be addressed.

Life-extension practices necessitate the collection of used products either through manufacturer takeback programs (e.g., OEM takeback of EoL electronics) or local collection sites, such as municipal programs. Standards can provide guidance for public and private collection programs, thereby increasing consistency. This in turn reduces confusion and promotes consumer participation and trust in the recovery system. Additionally, recovery processes, especially repair and refurbishment, necessitate access to information, replacement parts, and tools. Standards can be developed with participation from manufacturers to ensure these assets are available for recovery without compromising trade secrets. Another critical area for standards development is performance metrics and test methods for second-hand, repaired, refurbished, and remanufactured products. Such standards can certify the durability, functionality, and overall reliability of these products, and therefore increase consumer confidence and market development.

Standards are needed to support the sustainable use of products, such as guidance for efficient battery charging, or textile care instructions to minimize microfiber release. Standards can also support product reuse and repurposing, including quality specifications for resale as well as guides for repurposing products or components. For example, when the capacity of electric vehicle batteries is no longer sufficient to power vehicles alternative uses can be found such as grid-energy storage or small-format mobility (e.g., electric wheelchairs). Standards are needed to facilitate testing and decision-making for the most appropriate pathway and may involve battery chemistry, form factor, and history.

Standards are also needed to foster repair, refurbishment, and remanufacturing. Specifications for repair services would enable widespread product repair and consumer trust in opting for repair services for already owned products, as well as purchasing repaired products. Another approach to increasing consumer participation in used markets is the creation of a publicly available standardized repairability score or certification system that is comparable across product types. For instance, in January 2021 France instated a repairability index for select electronic devices aimed at both informing consumers at the point of purchase about how repairable the product is as well as pushing manufacturers to sell more repairable products to improve their score (International Telecommunication Union 2021).

Focus	Description
General	– Facilitate manufacturer take-back programs for resale, repair, and remanufacture: e.g., mail-in, store drop-off, pick-up or onsite decommissioning – Determine the role of digital twins in repair/remanufacture recovery – Determine the availability of information, replacement parts, and tools needed for repair – Performance metrics and test methods for quality assessment of repaired/remanufactured products – Ways to share safety implications associated with repair/remanufacture: e.g., presence of hazardous materials – Definitions and requirements for recovery terms: reuse, repurpose, repair, refurbish, remanufacturing – Certification programs for recovery processes – Guidelines for repair and remanufacture, including responsible party
Use, Reuse, & Repurpose	– Information sharing regarding product use and care to consumers – Quality specifications and performance metrics for reuse – Repurposing of products, components, or materials – Support tools and processes for material repurposing
Repair	– Create a publicly available repairability score – Repair service requirements
Refurbish & Remanufacture	– Manufacturer take-back processes for remanufacturing – Performance metrics of remanufactured products

Table 10 Standards for Back-End Recovery in a CE

6.6 Recycling Standards

Given the interest in recycling related standards at the workshop and the maturity of the industry compared to the other back-end recovery practices, standards specific to recycling are discussed separately from other back-end recovery efforts. Many opportunities exist to improve the collection, sorting, and materials preservation aspects of recycling. The standards depicted in **Table 11** are necessary to implement many of those improvements.

A focal area for improvement is the harmonization of collection and sorting infrastructure, particularly for municipal recycling programs. As discussed previously, recycling programs across the U.S. vary greatly, in part because the material recovery facilities (MRFs)—where materials collected for recycling are sent—have unique processing schemes and equipment. Harmonizing the process of matching the supply with the demand—e.g., matching a factory with a certain type of scrap to a recycling facility with the capacity to process that scrap—would go a long way towards increasing not only the quantity, but also the quality of recycled output. Standards could play a key role in this by providing guides for effective collection mechanisms and MRF processes and equipment. Additionally, in many cases there are multiple recycling pathways, and guidance is needed to support decision-makers on the most efficient and value-retaining pathways for their recycled materials.

ASTM could play an important role in creating application-specific quality and performance standards for recycled content where necessary, including how many times a material can be safely and effectively recycled depending on its next use. These standards could include metrics for material properties and performance—depending on the application, these may include bendability, puncture resistance, and other measurable properties—that are important for manufacturing and resulting products' functionality.

Focus	Description
Collection for Recycling	– Product/packaging collection for recovery – Collection infrastructure for municipal recycling programs (e.g., roll carts, drop-off containers) – Decision-making guidance on circular pathways selection for recovered materials/products
Sorting	– Categorizing sorting facilities according to their infrastructure capabilities (to handle different materials, sorting quality, capacity...) – Standard Operating Procedures for sorting process and equipment to remove contaminants/impurities – Defining categories for sorting output (e.g., MRF bale quality, types of plastics, types of textiles)
Recycling	– Removal of impurities during recycling processes (e.g., contaminants, cross-over materials, odors) – Recycling uncommon materials (e.g., ones not included in municipal collection programs) – Recycling technology selection for materials (e.g., mechanical, chemical) – Accounting of recycled materials and associated claims (e.g., mass balance accounting)
Recycled Content	– Guidance for the application and markets for recycled content – Recycled content claims – Quality and performance evaluation of recycled materials (e.g., bendability, puncture resistance, crushability, strength)

Table 11 Standards for Collection, Sortation, and Recycling

Recycled material-specific standards are being established in certain areas (e.g., *ASTM D5491-08 (2022)*, a classification of sources for recycled post-consumer polyethylene film, and *ASTM D5577-19*, a guide for separating and identifying contaminants in recycled plastics). There are existing standards that evaluate the quality and performance of materials (e.g., ASTM D5748-95 (2019) for testing the puncture resistance of plastic film wrap; and *ASTM F610M-21* for evaluating the quality of PVC piping). However, these do not specifically focus on recycled materials, or the concerns industry may have about whether testing recycled materials using the typical (i.e., available standard) testing methods is enough, or whether it should be tested using specialized (and perhaps stricter) standards that account for more prominent failure modes of recycled content.

A prior ASTM publication (ASTM STP 1540) discusses the testing and specifications needs for recycled materials in geotechnical construction. Other standards bodies such as the American Association of State Highway and Transportation Officials (AASHTO) have also set application-focused specifications on the use of recycled materials (e.g., AASHTO M295 and AASHTO M302). Such recycled content specific standards could provide ways to achieve the verification necessary for industry to use recycled materials with more assurance and to establish trade codes for U.S. imports and exports. As new standards for recycled materials are being developed, it will be important to establish consistency across the content of those standards (e.g., to address the characteristics highlighted in **Table 11**).

The standards in **Table 11** could further help stabilize the markets for materials such as recycled plastic, which currently suffers from instability and price volatility. Workshop participants pointed out that the cotton industry does not have any recycling standards; this and other industries without recycling standards could be potential partners for ASTM. Standards could include guidelines for specifying material-specific recycling and reuse guidance. This area serves as another opportunity for “standards for standards”.

7 Next Steps

Standards setting is complex and involves technical, business, and regulatory solutions. Standards are rarely static, rather they evolve over time as new knowledge is gained, solutions are found to business hurdles, and in the case of sustainability, more communal will is established. A strategy for pursing new standards is to start small and build on a standard as consensus can be reached. Over time a suite or suites of standards can be developed that will help secure our futures from the deleterious effects of current practices and provide a foundation for a more robust world. Building codes serve as the model for how this standardization could be achieved. As those codes evolved, so did buildings, with the buildings of today being designed and built to better withstand natural disasters than ever before in history. Similarly, new suite(s) of standards will be needed to embrace the new era of circular economy.

Standards development is a multipronged process of identifying topics, enlisting stakeholders and champions, embracing and directing research, and preparing for deployment of new standards. Figure 13 shows how the standards setting activities need to be complimented with research, education, and training programs. As new standards are established the research community will continue to build new subject matter knowledge, educate the next generation on existing practices, and look to the future to identify and solve emerging challenges. Concurrently, institutions such as ASTM and others will continue to evolve the standards through application and continuous improvement. Educational programs will be needed to bring the new standards into wide-spread practice, while certification programs will ultimately be needed to ensure that the standards are being used accurately and meeting the needs that they were designed to address.

Figure 13
Roadmap for ASTM subcommittee E60

While the solutions to many topic areas identified at the workshop will be complex, first steps can be identified and taken. For instance, in the area of designing products for circularity, principles can be established to integrate life cycle thinking into existing practices with forethought regarding EoL options for those products. While a fully robust solution to this problem is not yet known, some fundamental principles could be agreed upon today and expanded as more knowledge is gained. In the future, when recovery technologies and infrastructure have advanced, the principles can be updated and expanded to better reflect the evolving environment. Similarly, standards around classification of discarded materials, which E60.13 has already established, can be expanded to better support material marketplaces.

While each of the areas outlined at the workshop has a complex set of needs, foundational standards can be initiated to address the domains. Within ASTM, standards fall into categories similar to those highlighted in Table 2.

Noteworthy is that many early standards are developed as “Guides” meaning they are recommendations of good approaches that can be adopted by industry. As the experience and knowledge surrounding these practices matures, the best aspects may be further refined as a “Practice” or “Specification” standard. These require more rigor in the standards requirements such that they may be suitable for use in a testing and certification program. This approach to setting standards allows for progressive development as an area matures.

Research challenges exist for many of the topics discussed and more work will be needed to develop robust solutions. New standards with foundational content can establish a baseline of understanding and consensus on which new research can be initiated, while also educating the broader public about the approaches, terminology, and vision. As stakeholders converge on solutions to these open questions, early initiation of standards can provide the pathway by which those solutions can be scaled up. Some of the open topic areas that were highlighted during the workshop are shown in **Table 12**.

Research Needs	
– Definitions for a digital thread to support traceability of materials across the life cycle	– Principles for specifying requirements for and reliability of recycled materials
– New metrics for environmental, social, and economic impacts of a CE	– Methods for characterizing and assessing recycling practices to identify best practices: e.g., survey of process schemes and equipment (see section on needs for recycling)
– Modeling techniques to predict potential impacts on system dynamics as new material streams are brought online	– Methods for identifying optimal recovery options for a given organization and/or material type
– Methods to formalize data collection and reporting, such as for carbon and other sustainability accounting requirements	– Metrics for calculating the environmental impact of participation in secondary materials marketplaces, e.g. avoided carbon emissions
– Methods for identifying life cycle impacts at design time	– Assessment methods for new business models such as eco-industrial parks where industrial neighbors can create symbiotic relationships that reduce overall impacts
– Measurement practices for comparing material impacts	– Metrics and methods for collecting data to predict content, quality, and recyclability of “waste” streams
– Evaluation methods for assessing emerging, less traditional materials where the life cycle impacts are not fully understood. For example, bio-based, compostable, and regenerative options are all gaining significant interest, yet more research is needed on their material properties and life cycle impacts before designers should consider their use at scale	– Understand potential externalities in the transition to a CE. Possible drawbacks to keeping materials in the economy need to be identified, including how to measure and mitigate them. For example, methods and data are needed to assess the energy demand associated with transitioning to and maintaining a CE. In addition, the transition to CE will be disruptive to many industries and current practices and need mitigation strategies

Table 12 Research needs identified in workshop

The next step for ASTM E60 is to develop leadership and engagement in the area of CE for manufacturing materials and to pursue the types of standards identified herein. ASTM E60 will initiate new work items to address some of the standards identified and they will work with other ASTM committees to best understand how unified solutions can be developed.

ASTM Committee E60 is well-positioned to address some of the needed standards identified in Section 6 and to coordinate with other ASTM committees or standard development organizations that may be more appropriate for select standards or focus areas. Since the workshop, E60 has initiated efforts to engage more stakeholders and initiate standards. A round-table of committee leaders across ASTM was held to share information and identify areas for collaboration between committees. One idea that has emerged is the development of standards for standards which can provide guidance for the plethora of new efforts that will need to be undertaken across material types to address efforts to bring those materials back into the economy. As an example, the recently published E60 standard *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 International 2022g) illustrates how such a standard-for-standards might work. This guide builds on established practices for LCA and illustrates good methods for accounting for recycled materials within that standards framework. The base of the standard does not reference any particular material, but it includes appendices for eight different material types that apply the base method, adding the nuances needed for those specific materials. As a result of the workshop, E60 initiated a new work item for Circular Product Design which will be modeled after the approaches taken in E3199. The standard will contain a core set of principles with appendices for different product types.

In general, standards will be critical for wide-scale deployment of new practices for manufacturing in a circular economy. With appropriate standards, not only can industry begin to deploy new practices, but work can also be initiated on designing the education, training, infrastructure, and certifications that will be necessary as we progress towards a CE. Stakeholders across the manufacturing sector—e.g., material and product designers, manufacturing processors, and recovery processors—came together in ASTM's workshop and survey to identify standard needs. ASTM, the larger manufacturing sector, and the world will rely on these learnings to bring a CE vision into fruition. At the same time, investments must also be made to train the next generation of professionals to identify, tackle, and deploy solutions to the challenges that emerge as we move forward in building a sophisticated circular ecosystem.

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Author Contributions

KCM and AC conceived the workshop and survey. KS, MR, and NL designed the survey and analyzed the results. All authors contributed to the planning and execution of the workshop.

KS and NL wrote the original report draft and revised according to reviewer comments. KCM and AC oversaw the process and KCM reviewed and revised the original draft. BH, NM, VF, and MR contributed to Sections 2 and 6.

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Appendix A: Survey Questions and Responses

Q1: What is the scope of the organization for which you are responding?

Answer Choices	Responses	
Manufacturer with a single facility	20.00%	52
Single facility within a larger company	10.77%	28
Multiple facilities within a single company	45.38%	118
Manufacturing partner (e.g. professional society, association, or consultant)	23.85%	62
TOTAL		**260**

Q2:` How big is the organization for which you are responding?

Answer Choices	Responses	
0–19 employees	15.27%	40
20–499 employees	35.50%	93
500 or more employees	49.24%	129
TOTAL		**262**

Q3:` In which region is your organization's headquarters located?

Answer Choices	Responses	
North America	80.53%	211
South America	0.00%	0
Europe	9.54%	25
Asia/Middle East	8.02%	21
Africa	0.38%	1
Australia/Oceania	1.53%	4
TOTAL		**262**

Q4: In which regions are your organization's manufacturing operations located?

Answer Choices	Responses	
North America	91.30%	231
South America	20.95%	53
Europe	33.99%	86
Asia/Middle East	37.94%	96
Africa	9.88%	25
Australia/Oceania	14.23%	36
TOTAL RESPONDENTS: 253		

Q5: Which industry/industries are you a part of?

Answer Choices	Responses	
Chemicals	22.69%	59
Computers and Electronics	6.92%	18
Electrical Equipment, Appliances, and Components	10.00%	26
Food and Beverage	7.31%	19
Furniture and Related Products	5.77%	15
Leather and Allied Product	1.54%	4
Machinery	13.46%	35
Metals and Minerals	13.08%	34
Petroleum and Coal	3.85%	10
Plastics and Rubber	41.54%	108
Printing and Related Support Activities	5.00%	13
Textiles and apparel	6.54%	17
Transportation Equipment	9.23%	24
Wood and Paper	8.08%	21
Building Products	23.85%	62
Other	20.77%	54
TOTAL RESPONDENTS: 260		

Q6: To what extent does your organization incorporate sustainable manufacturing or circular economy into your practices or planning processes?

Answer Choices	Average Number	Total Number	Responses
Responses	64	16,277	254

TOTAL RESPONDENTS: 254

Q7: **Motivators for implementing more sustainable practices.**

Answer Choices	Responses	
Customer expectations	67.05%	173
Customer retention	29.84%	77
Branding/reputation	53.88%	139
Cost savings	50.78%	131
Corporate goals	61.63%	159
Alignment with emerging industry non-regulatory standards	36.43%	94
Alignment with regulatory and legal requirements	52.33%	135
Tax incentives (e.g energy reduction)	18.22%	47
Employee engagement	29.07%	75
Social concerns around pollution and climate	61.24%	158
Risk management	32.56%	84
Other	5.04%	13
TOTAL RESPONDENTS: 258		

Q8: **Barriers to implementing more sustainable practices.**

Answer Choices	Responses	
Predictability or reliability of marketplace of recycled materials	53.36%	135
Concerns around material quality in using recycled content (contamination, content, etc)	57.71%	146
Lack of knowledge about circularity	28.85%	73
Lack of non-regulatory and technical standards	29.25%	74
Lack of policies related to circular economy	35.57%	90
Lack of educational resources	21.34%	54
Cost to implement	60.08%	152
Technological barriers	46.64%	118
Employee engagement	9.09%	23
Resistance to change	29.25%	74
Other	12.65%	32

TOTAL RESPONDENTS: 253

Q9: When your facility manufactures a product do you consider alternative manufacturing approaches based on environmental impacts beyond those that are regulated?

Answer Choices	Responses	
Yes (please explain)	64.00%	160
No (please explain)	37.20%	93

Q10: Does your company directly produce energy?

Answer Choices	Responses	
No	88.79%	206
If yes, then is any of the energy sold or does it all get used internally?	11.21%	26
TOTAL		**232**

Q11: How do your manufacturing operations address the use of recycled materials?

Answer Choices	Responses	
We try to use recycled materials where possible	67.61%	144
We set targets for % of recycled materials used.	25.82%	55
We set targets for landfill diversion.	24.41%	52
We actively seek alternative uses for our bi-products.	40.85%	87
Other	21.13%	45

TOTAL RESPONDENTS: 213

Q12: Beyond manufacturing, how does your company address circularity?

Answer Choices	Responses	
We buy back or take back goods and reuse the products	26.73%	54
We remanufacture or refurbish goods and/or parts	26.73%	54
We plan for reuse of the packaging materials used in our product delivery processes	23.76%	48
We develop relationships with others to reuse our discarded materials (i.e. waste, scrap, etc)	60.40%	122
Other	26.24%	53

TOTAL RESPONDENTS: 202

Q14: Do you measure the percentage of waste materials you divert to recycling?

Answer Choices	Responses	
No	59.52%	125
If yes, what is that percentage?	40.48%	85
TOTAL		**210**

Q15: Do you have measurable circular economy or waste reduction targets?

Answer Choices	Responses	
No	65.09%	138
If yes, please describe.	34.91%	74
TOTAL		**212**

Q16: How does your facility handle used packaging materials?

Answer Choices	Responses	
Recycle within the company	33.01%	68
Send to a professional recycler	60.68%	125
Return to the supply chain partner	17.96%	37
N/A	22.33%	46
TOTAL RESPONDENTS: 206		

Q17: What do you do with by-products of your primary production processes?

Answer Choices	Responses	
Use in house	55.10%	108
Resell to Market	37.24%	73
Provide Partner	16.84%	33
Provide to Recycler	57.65%	113
Landfill	48.47%	95

TOTAL RESPONDENTS: 196

Q18: Does your company up-cycle or sell up-cycled products? (Definition of "upcycle": To recycle something in such a way that the resulting product has a higher value/quality than the original product.)

Answer Choices	Responses	
No	77.78%	161
If yes, how?	22.22%	46
TOTAL		**207**

Q19: Are decisions to factor in sustainability overseen from the management level down?

Answer Choices	Responses	
Yes	81.82%	153
No	18.18%	34
TOTAL		**187**

Q20: Do you have specific sustainability goals for the organization?

Answer Choices	Responses	
Yes	62.03%	116
No	37.97%	71
TOTAL		**187**

Q21: Do you have specific recycling and/or reuse goals for the organization?

Answer Choices	Responses	
Yes	46.77%	87
No	53.23%	99
TOTAL		**186**

Q24: Does your company report on non-regulatory environmental metrics?

Answer Choices	Responses	
Not at this time	61.67%	111
Greenhouse gases	28.33%	51
SASB	6.67%	12
Other	17.78%	32
TOTAL RESPONDENTS: 180		

Q25: Does your company currently use the below ISO management standards to improve efficiency?

Answer Choices	Responses	
ISO 9001 for quality management, which helps to reduce scrap and waste through tighter control over processes	71.54%	93
ISO 14000 series on environmental management, which defines practices for establishing an environmental management system	45.38%	59
ISO 50001 on energy management	16.92%	22
Other	30.00%	39
TOTAL RESPONDENTS: 130		

Q26: Have you considered the new ASTM standards for Sustainable Manufacturing? Click here for more information.

Answer Choices	Responses	
Yes, we are using at least one of the new standards.	2.87%	5
Yes, we are currently evaluating them.	16.67%	29
Yes, we have evaluated and are considering whether or where to apply.	11.49%	20
No	71.84%	125
TOTAL RESPONDENTS: 174		

Q27: Are you implementing or are planning to implement circularity across any of the following product life cycle phases or business units?

Answer Choices	Responses	
Design	25.95%	34
Production operations	49.62%	65
Supply chain management	24.43%	32
TOTAL		**131**

Q28: Are you considering a service model for any of your products?

Answer Choices	Responses	
Yes	19.30%	33
No	80.70%	138
TOTAL		**171**

Q29: **Does your company intentionally design products according to circular economy principles — e.g. design for the environment, design for disassembly, etc.?**

Answer Choices	Responses	
Yes	46.86%	82
No	53.14%	93
TOTAL		**175**

Appendix B: Workshop Agenda

Time (ET)	Wednesday, April 20	Thursday, April 21
11:00–12:00 PM	Plenary 1: Manufacturing in a Circular Economy —KC Morris, NIST	Plenary 2: Accelerating the Transition to Circular Economy —Nabil Nasr, REMADE Institute
12:00–1:00 PM	Session 1: Foundations of an Industrial Circular Economy	Session 3: Circular Materials Management
1:00–1:45 PM	Roundtables	Roundtables
1:45–2:00 PM	Break	Break
2:00–3:00 PM	Session 2: Recycling Today and Tomorrow	Session 4: Designing Out Waste
3:00–3:45 PM	Roundtables	Roundtables
3:45–4:30 PM	Discussion	Discussion

Appendix C. Workshop Presenters

SPEAKERS		
Name	**Organization**	**Presentation Title**
Plenaries		
KC Morris	US National Institute of Standards and Technology	Manufacturing in a Circular Economy
Nabil Nasr	REMADE Institute	Accelerating the Transition to Circular Economy
Session 1: Foundations of an Industrial Circular Economy		
Minal Mistry	Oregon Department of Environmental Quality	Measurements that Matter
Mike Levy	First Environment	Impact of ISO TC 323 Circular Economy standards development on discarded manufacturing materials
Alberta Carpenter	US National Renewable Energy Laboratory	The Role of Life Cycle Assessment
Session 2: Recycling Today and Tomorrow		
Daniel Figola	Advanced Drainage Systems	Role of standards for end use of materials with recycled content and areas standard would be beneficial for recycled material intake
Mark Mistry	Nickel Institute	Circular Economy and Metals: The Case Study of Nickel
Vivian Tai	GS1 US	Standards to Scale Circularity: Persistent Identification for Recycling Tomorrow
Session 3: Circular Materials Management		
Andrew Mangan	US Business Council for Sustainable Development	Materials Marketplace
Domenic Decaria	Vinyl Institute	The Role of Recycled Content Standards in Circular Materials Management
David L. Wagger	Institute of Scrap Recycling Industries (ISRI)	The Impact of Specifications and Regulations on Circular Economy
Session 4: Designing Out Waste		
Zoé Bezpalko	Autodesk	Circular Design, Technology Tools, and Industry
Trina Matta	The Recycling Partnership	The Recycling Partnership
Brenda Martens	Light House	Circularity in the Built Environment — Designing for Disassembly

Appendix D: Overview of Presentations

Session 1

Minal Mistry, Oregon Department of Environmental Quality: *Measurements that Matter*

Minal Mistry focused on the origins of Industrial Ecology and how it aligns with the core principles of CE, i.e., preservation of natural resources, optimizing yields and designing our externalities. Based on his experience, he highlighted the existence of various sustainability frameworks to address pollution, waste, and sustainable materials management. At present, these along with CE lack a “peoples’ perspective”: while they focus on the environmental and economic pillars of sustainable development, they do not focus on the societal pillar. In terms of the challenges associated with codifying CE related standards, he mentioned the importance of using the tenets of CE, in combination with industrial ecology to answer questions pertaining to resource demand trends, toxic accumulation, rebound effects, producer responsibilities, and stewardship obligations. He also noted the importance of understanding the scale of environmental impacts as a consequence of manufacturing and developing standards that take this into account. Minal concluded his talk by underscoring the cascading impacts of the adverse impacts caused by manufacturing. These range from human rights violations, inequity and poverty, and the inadvertent creation of pollution havens.

Mike Levy, First Environment: *Impact of ISO TC 323 Circular Economy standards development on discarded manufacturing materials*

Mike Levy is a sustainability executive with First Environment and serves as a technical expert in the ISO Technical Committee 323 on CE standards. His talk provided an overview of the ISO and its role. The ISO is the global apex standards forming body that facilitates best practices and international trade between countries via the development of standards. The ISO TC 323 on CE standards was established in 2019; its scope is “standardization in the field of CE to develop frameworks, guidance, supporting tools and requirements for the implementation of activities of all involved organizations, to maximize the contribution to sustainable development.” Mike highlighted the importance of creating a mindset that supports a CE paradigm. Operational standards to implement CE globally, especially for small and medium based manufacturers (SMMs), are necessary in highly interconnected global supply chains. The presentation ended by reiterating ISO’s ability to impact global CE practices and the creation of complementary CE decision-making methods.

Alberta Carpenter, Ph.D., U.S. National Renewable Energy Laboratory: *The Role of Life Cycle Assessment*

Alberta ‘Birdie’ Carpenter is a researcher with the National Renewable Energy Laboratory (NREL). Her presentation reiterated the fact that CE is not a goal, but rather a tool to achieve sustainability goals. DoE/NREL have been working to implement CE via improvements in supply chains, the manufacturing sector and improved end of life (EoL) strategies, and by taking a product life cycle perspective to mitigate environmental impacts of a product. Dr. Carpenter’s presentation specifically explored LCA and discussed its application for decarbonizing the economy. In this regard NREL has undertaken the development decision-making tools based on integrated predictive modeling techniques that use LCAs to facilitate society’s transition to clean energy technologies. She also acknowledged that carrying out LCAs depends on how the problem is defined and the associated data inventories need to be standardized to eliminate inconsistencies and inaccuracies related to the data in those inventories.

Session 2

Mark Mistry, Nickel Institute: *Circular Economy and Metals: The Case Study of Nickel*

Mark Mistry is a senior sustainability manager at the Nickel Institute and the E60 task force leader for the developing "Recycling in LCA" standard. He discussed the circular economy of metals from the perspective of the nickel industry. He stated that the advantage of metals is that they can be recycled repeatedly without losing their properties. The specific material type has a large role in how it is recycled; metals are re-meltable and do not change in properties as a result. Moreover, metal recycling has multiple benefits such as being economically beneficial (materials are returned and not lost), having a better understanding of where and when materials occur at the end of life, and reducing the USA's need for imports. However, among the challenges that are faced are the increasingly complex articles and consumer products, which are difficult to recycle; consumer behavior education towards recycling, which is still a struggle; inefficient processes for the recycling and sorting of materials; and recycling yields.

Dan Figola, Advanced Drainage Systems: *Role of standards for end use of materials with recycled content and areas standard would be beneficial for recycled material intake*

Dan Figola is the director of product development at ADS (Advanced Drainage Systems) where they produce both virgin plastic and mechanically recycled plastic. He presented his experience with the roles standards for end use of materials with recycled content and areas where more standards would be beneficial for recycled material intake. He discussed the roles that standards play in recycling and circularity. The current standards available are: 3 ASTM standards and 1 AASHTO standard for finished product specifications, 1 ASTM installation specification, many ASTM standards for testing the production process and end product itself, and 1 ASTM standard test method for products made from PCR plastic.

Vivian Tai, GS1 US: *Standards to Scale Circularity*

Vivian Tai is the Innovation Manager at GS1 US. She discussed standards for material identity and their role in managing products and materials flows in a supply chain to support a Circular Economy. GS1 standards use 3 pillars for information which are: identify, capture, and share. The goal of a resilient economy is not using less but increasing circularity. She discussed the need to maintain a material's value across the value chain and the use of persistent identification, whereby a unique value is created that can be tracked throughout a product's life cycle. There should be historic data available on a product to understand its value and to trace it from birth to rebirth.

Session 3

Andrew Mangan, U.S. Business Council for Sustainable Development:
Materials Marketplace and Carbon Quantification

Andrew Mangan presented the work done by the U.S. Business Council for Sustainable Development (USBCSD) along with several organizations in different regions, including the Great Lakes region. The Materials Marketplace (MM) is one of these efforts, allowing companies to list their used or excess materials and network with other companies interested in buying them. The platform networks users from different regional programs in North America (e.g., Austin, Tennessee, Michigan, Ohio, Ontario, and Washington). Work is currently being done in collaboration with the National Institute of Standards and Technology (NIST) to quantify the carbon emissions avoidance due to the MM transactions and understand the allocation of that "carbon saving" between the buyer and seller. Given the interest shown by the MM users, such a measure will encourage more companies to participate in the MM, thus growing the CE.

Domenic DeCaria, Vinyl Institute: *The Role of Recycled Content Standards in Circular Materials Management*

Domenic Decaria presented some of the current recycling-focused standards work being done at ASTM. As the U.S. and Canadian vinyl industry is targeting a 10 % increase in recycling by 2025, scaling-up will require an industry-wide consensus on vinyl materials with recycled content. In the industry, the compound formulators and product engineers can improve the recycling potential by formulating materials that better integrate recycled content and improving the product designs' material efficiency. Also, the procurement and marketing teams can investigate identifying alternative sources of secondary materials that are specifiable and usable by the formulators. ASTM's new standard D20.95, currently being developed, guides material characterization and informs the users in selecting appropriate material for the performance requirement.

David Wagger, Ph.D., Institute of Scrap Recycling Industries (ISRI):
The Impact of Specifications and Regulations on Circular Economy

Dr. Wagger, given his experience working in the Institute of Scrap Recycling Industry (ISRI), provided an overview of how specifications and regulations can impact the broader CE. ISRI takes the view that recycling should be driven by markets and flow as commodities rather than as a part of waste management. To enable this, ISRI has been developing the Design for Recycling concepts since the mid-1980s. Some of the main ideas include factoring the EoL practices at the beginning and making the designs simpler. Since recycling is a high volume, low margin business, scale is essential to make recycling more economical. That is where specifications such as ISRI Scrap Specifications Circular (Institute of Scrap Recycling Industries, Inc. 2022) can help. By providing specifications and guidelines on various processed scrap commodities (including ferrous, nonferrous, paper, plastics, electronics, rubber, and glass), it helps to create more opportunities to repurpose the material (i.e., a market). Dr. Wagger also discussed the Resource Conservation and Recovery Act (RCRA) and its limitations. RCRA does not define "recycling." Another limitation is how it has allowed different localities to implement waste management differently, creating a fragmented waste management infrastructure in the US

Session 4

Zoé Bezpalko, Autodesk: *Circular Design, Technology Tools, and Industry*

Zoe led the session with a discussion on technology that enables designers to consider sustainability and circularity. Right now, built environments account for ~40 % of total carbon emissions, while manufacturing only accounts for 20 %. Furthermore, 80 % of environmental impacts are baked in during the conceptual design phase of product. Thus, there is a great responsibility to enact circularity thinking during the critically impactful early design stage.

As of now, Autodesk has identified three personas responsible for the product design: the product designer, the mechanical engineer, and production engineer. These three personas often work in a vacuum or only interact from product designer to mechanical engineer and mechanical engineer to production engineer. However, there are various design elements that can be used across all personas and in other areas of the product life cycle. Autodesk is focused on capturing, connecting, and facilitating collaborate spaces for these personas to seamlessly interact. In return, circular product design will lead to better designs, better material utilization, and data management.

Autodesk has explored two case studies to enact circular initiatives with industry partners. Working with 57st. Design, Autodesk has attempted to create a platform for furniture design that accounts for corporate responsibility, including takeback programs. In this case, furniture designs must be recyclable, trackable, and created with reusable parts. The second use case is with Kartell. Kartell and Autodesk are working together to create a generative design platform that gives design suggestions for material reduction and material adaptably (how does the design change with different materials but static design constraints).

Trina Matta, The Recycling Partnership: *The Recycling Partnership*

Trina's presentation focused on increasing the robustness of recycling programs in the United States and packaging design. This presentation represents just one of the systems that circular products need to address during the product life cycle. As EoL systems become more advanced, product designers need to envision how products will interact with these systems. In this case, product packaging, with a short life cycle, is a product that heavily interacts with local municipalities. The goal of the Recycling Partnership is to improve the U.S. recycling system through:

– Providing equitable and informed access to recycling
– Advancing Circularity
– Accelerating with policy
– Leveraging data for systems and product design

The Recycling Partnership promotes a cohesive network of thought leaders across the sector called the Circularity Council. The Circularity Council brings together industry stakeholders to bring clarity and consensus to how recycling systems may move forward towards a Circular Economy. The current task of the council is to create a recyclability framework with focus on product packaging.

The first iteration of the framework is completed and focuses on five areas:

1. **Design for Circularity:** The council is working on recyclability guides and design guidelines that implement post-consumer content, package reduction, and utilize circular material streams.

2. **Recyclability Prevalence:** Right now, 70% of market volume for packaging is recyclable. However, not all packaging is recycled or not recyclable at all (mixed material packaging). Here the council aims to increase the recyclability of packaging to 100% and close the gaps between recyclability and recycling rate.

3. **Access + Adoption:** In this area, the framework is tooled to inform on the general availability of recycling programs in the US. By profiling the municipal recycling programs across the nation, enterprises can design packaging that would most likely be recycled across the nation or within targeted geographical regions.

4. **Capture Journey:** This area is focused on the storability of packaging, highlighting design guidelines that increase the sortablity of product packaging in correspondence to the general capabilities of local municipal recycling systems.

5. **Packaging Fate:** Finally, the circularity council advocates for package designs that are easy to recycle. The framework provides information on providing enough information for consumers and recyclers to properly process the packaging. This area of the framework also looks at end markets and industry need for the processed materials.

Brenda Martens, Light House: *Circularity in the Built Environment — Designing for Disassembly*

Brenda's presentation focused on buildings as large products that have high complexity and long life cycles. The building sector works aggressively towards making building operations net-zero. However, the commercial building sector produces almost an equal amount of greenhouse gases as the residential sector. Most of these emissions are caused by embedded carbon within the building materials, construction waste, and increased material usage.

As Brenda demonstrated, some existing certifications can contribute toward the transition toward a CE for buildings. For example, LEED and TRUE certifications are focused on qualifying projects as sustainable and contributing zero-waste. Future CE building certifications need to have a cradle-to-cradle scope and be well supported by standards. Future certifications should build on the five areas listed below

1. **Material Health**
    a. Certify materials knowing all ingredients of the material.
    b. Identify materials as biological or technical.
    c. Understand how chemicals and material ingredients impact human health.

2. **Material Re-utilization**
    a. Design products that can be safely returned to nature.
    b. Maximize usage percentage of rapidly renewable resources.
    c. Maximize percentage of material that can be readily reused, recycled, or composted at EoL.

3. **Renewable Energy & Carbon Management**
    a. Move towards 100% renewable energy sources.
    b. Purchase carbon offsets.

4. **Water Stewardship**
    a. Ensure water leaving the facility is as clean or cleaner than that coming in.
    b. Increase water usage efficiency.

5. **Social Fairness**
    a. Ensure that there is a positive impact on local and global communities.

Appendix E: International and National Trade Codes, Administrators, and Criteria for New Codes

Harmonized System (HS) codes (HS codes) is a standardized numerical method of classifying traded products and is used by customs authorities around the world to identify products when assessing duties and taxes and for gathering statistics (International Trade Administration 2022). The HS assigns specific six-digit codes for varying classifications of commodities which serve as the foundation for the import and export classification systems used in the U.S. The U.S. import classification system, known as the Harmonized Tariff Schedule (HTS) is administered by the U.S. International Trade Commission (USITC), whereas the U.S. export classification system, known as the Schedule B, is administered by the U.S. Census Bureau, Foreign Trade Division. Both the HTS and Schedule B rely on the international HS codes for their 4- and 6-digit headings and subheadings. But both the HTS and Schedule B are longer, 10-digit codes to provide more refined categorization of imported and exported products. Though matched at the 6-digit HS level, Schedule B and HTS codes for products may not be the same up to the 10-digit level; in fact there are more HTS numbers than Schedule B numbers, reflecting a greater amount of detail on products imported into the U.S. (International Trade Administration 2022).

While the process of establishing new international HS codes can take five years or more, the process is faster for HTS and Schedule B codes which can generally be performed in less than year. The USITC is the manager of the Section 484(f) Committee, an interagency committee made up of representatives from the USITC, U.S. Customs and Border Protection (USCBP), and the U.S. Census Bureau. The 484(f) Committee tries to serve the trade data needs of both government and private data users by adding, removing, or modifying the statistical reporting numbers in the HTS and Schedule B. Additionally, the committee can modify required reporting units and other information that shippers are asked to provide. The committee uses the following criteria when considering the establishment of new HTS and Schedule B codes:

– Each proposed 10-digit statistical category must cover a product or a grouping of goods typically having a $1 million annual trade.
– The proposed annotation must have a clear and administrable description.
– There must be at least 3 importers or exporters reporting shipments in the proposed category on an average monthly basis to avoid disclosure of confidential information.

Efforts have been made to create new HTS codes for recycled PET resin. Specifically, a request was made in 2019 to add statistical breakout codes for three categories of PET with varying degrees of recycled content (0 %, up to 50 %, and more than 50 %). However, the request was rejected on the basis that the proposal would not be administrable because USCBP would have no way to determine if a PET resin is made from recycled inputs (i.e., they cannot verify whether a product contains recycled content) (Kelley Drye & Warren LLP 2019).

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ASTM INTERNATIONAL HEADQUARTERS

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

TEL	+1.610.832.9500
FAX	+1.610.832.9555
EMAIL	SERVICE@ASTM.ORG
WEB	WWW.ASTM.ORG