Circularity for Secure and Sustainable Products and Materials

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Executive Summary

The current economic model, both in the United States and globally, is largely linear; resources are extracted, products are manufactured and used, and then they are discarded. This linear model results in substantial carbon emissions, energy use, resource extraction, waste generation, environmental degradation, and loss of valuable materials from the economy. The negative impacts of extraction and waste generation are often felt more acutely by marginalized populations. Additionally, existing global supply chains struggle to adapt following disruption. Demand for materials is increasing at a rapid pace and with it, the associated environmental and societal burdens. The concept of a circular economy has been proposed as a more sustainable alternative to a linear economy. Product and material circularity, which involves minimizing life cycle environmental impacts through recirculation of products and materials in the economy, is essential for realizing the economic, environmental, and societal benefits of a more circular economy.

Increasing product and material circularity is also a critical enabler of the U.S. Department of Energy (DOE) Office of Energy Efficiency and Renewable Energy's (EERE's) mission. Circularity contributes to decarbonization by expanding the supply of critical materials needed for the clean energy transition and extending the lifetime of clean energy technologies. Circularity improves material efficiency, which reduces energy demand related to raw material extraction and manufacturing processes, contributing to economywide decarbonization and reducing the associated environmental burden felt by local communities. Creating circular supply chains in the United States strengthens the U.S. manufacturing ecosystem by creating secure, domestic supplies of critical materials; expanding the manufacturing workforce; and creating better-paying, higher-skilled, and safer jobs than traditional waste management. In addition to the direct benefits of job creation, increased product and material circularity can make U.S.-manufactured products more competitive globally.

This draft identifies unique challenges and potential solutions related to recirculation of products and materials, at their end-of-use (EOU) or end-of-life (EOL) back into the economy. This document aims to describe the potential economic and environmental impact of increasing product and material circularity approaches, strategies, and technologies and to communicate EERE's objectives in this space. It identifies opportunities, challenges, and enablers for advancing circularity. Finally, this strategy document provides an overview of current efforts across EERE and future focus areas for activities and investments to advance product and material circularity.

Product and Material Circularity Advances the Mission

Figure ES-1 illustrates how advancing product and material circularity by creating circular supply chains helps the United States to capture the strategic opportunities offered by a more circular economy and realize positive impacts on decarbonization, community benefits, security of U.S. supply, and job creation. Previous EERE investments are already having an impact across the mission space by advancing technologies toward deployment and influencing investment and decision making.

Product and material circularity is a strategic opportunity to:

- Minimize environmental life cycle impacts of U.S. manufactured products.
- Reduce the burden on local communities from material extraction and processing.
- Increase supply chain security and resilience.
- Strengthen domestic manufacturing and create good jobs.
- Lead in the development and commercialization of end-of-life processing technologies.

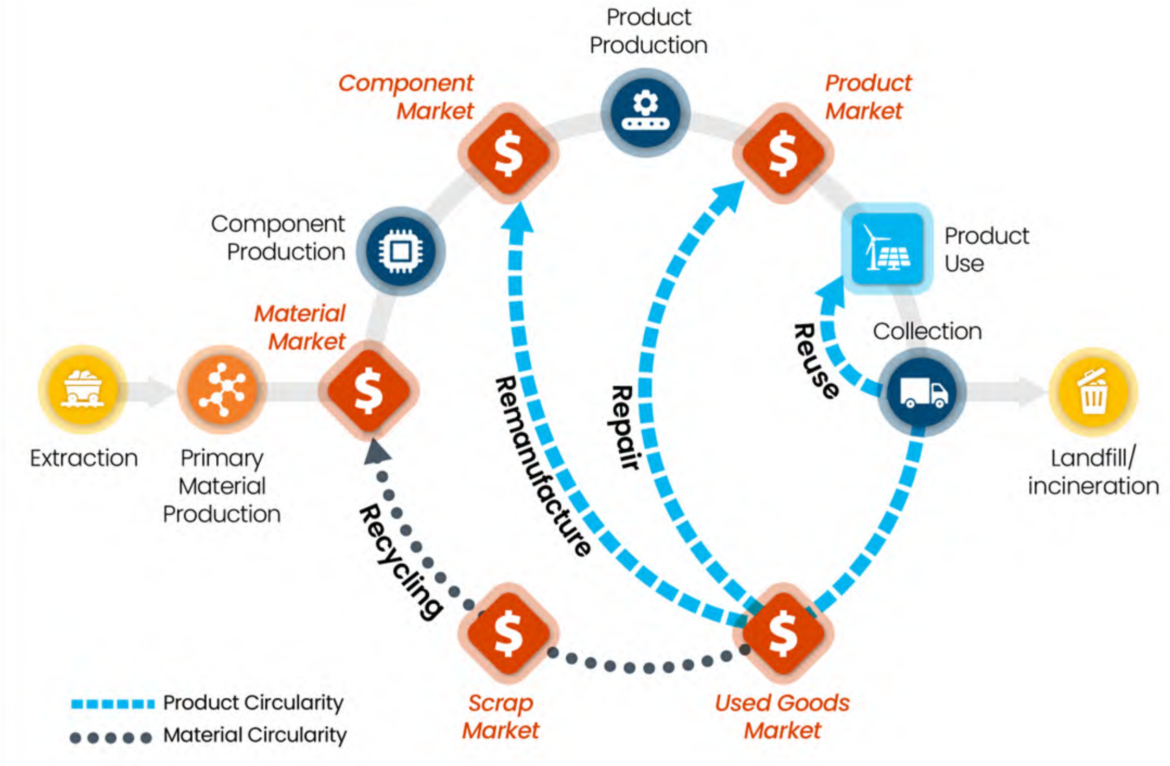

Figure ES-1. Illustration of strategic opportunity for EERE shows how increasing product and material circularity directly contributes to decarbonization, community benefits, U.S. security of supply, and job creation. EERE investments to increase circularity can bend our linear economy into a more circular future.

Current Focus Areas

In this strategy we distinguish between products, which are goods sold to consumers, and materials, which are the building blocks of those products. This was done because often different strategies are needed to increase the circularity of products than their constituent materials, although strategies like design for circularity can apply to both. There are substantial efforts across EERE to advance the circularity of products and materials. Multiple offices have activities related to product and material circularity that are complementary in addressing specific focus areas.

Current EERE focus areas include:

- Materials needed for clean energy technologies, such as critical materials and composites.
- Materials with a large energy and emissions footprint, such as: steel and aluminum, construction materials, and plastics.
- Products whose reuse, repair, refurbishment, and/or redesign could significantly reduce economywide energy and carbon emissions, including buildings, batteries, wind turbine blades and nacelles, solar panels, vehicle components, electrolyzers, and fuel cells.
- Cross-cutting enablers that accelerate technology deployment and guide sound decision making, such as consortia that promote innovation ecosystems, shared facilities, and analysis, including models and data.

Future Work To Advance Product and Material Circularity

Because of the large variety of approaches to increasing circularity across the economy, this strategy also presents a framework for how EERE will prioritize which activities to focus on to drive real world impacts. This framework includes a three-step approach comprised of:

- Assessing potential impacts of increasing circularity for a product or material to prioritize products and/or materials with highest potential impacts.
- Identifying the transformation pathway and the barriers to deployment.
- Considering the timeline for deployment and scaling.

Continued, coordinated efforts and investments are needed across EERE to overcome the substantial challenges identified and discussed in this strategy. Future EERE efforts will include developing technologies that unlock product and material circularity as well as supporting technical assistance, data, and tool development to support decision making. The technology advancement and analysis will focus on cross-cutting areas that lower costs, increase speed of circular supply chain development, and deliver maximum benefits, such as:

- Developing more rapid and cost-effective product, component, and material identification, sortation, and separation technologies which can lower costs, improve quality, and enable economically viable circular supply chains.
- Increasing recovery and reuse of critical materials to enable more rapid deployment of clean energy technologies.
- Unlocking design for circularity, which includes design and material approaches to enable product and material circularity and leveraging digital tools and approaches for system monitoring, assessment, and tracking.

Analysis and the development of analytical and decision-making tools will focus on activities that improve decision making to drive maximum impact. This may include developing data, analysis, and modeling tools to support whole life cycle analysis and support decision making, including at the product and business model design stage.

Policy and business model innovation will be essential in transitioning technologies into the marketplace to have a national-scale impact. Additional work is needed to marry this evolving landscape with research direction to accelerate deployment and amplify impact. As part of that effort, EERE will continue to actively coordinate and engage across DOE, the federal government, and with external stakeholders. Collaboration and engagement activities will focus on:

- Ensuring that fundamental insights and discoveries inform and are incorporated into EERE programs via active engagement with the DOE Office of Science, the Advanced Research Projects Agency – Energy, the National Science Foundation, and the wider research community.
- Coordinating and aligning with the DOE Office of Infrastructure and other agencies to ensure technologies advance through EERE efforts progress toward deployment and adoption.
- Providing technical assistance to support the transition to more circular approaches.
- Leveraging EERE's convening power to foster collaboration among stakeholders to facilitate design of circular products, systems, and ecosystems.

Actively engaging across the interagency to support activities including the Buy Clean Initiative, the Federal Life Cycle Assessment Commons, and the national recycling strategy. Together, these efforts provide incentives, tools, and strategies to implement circularity technologies and initiatives.

Increasing product and material circularity is critical to EERE's mission and is an important area of investment for achieving both DOE and national energy and climate goals. By providing an overview of current EERE efforts as well as a framework for prioritizing future investment related to advancing product and material circularity, EERE aims to increase stakeholder awareness, engagement, and alignment that will ultimately drive national-level impacts. As this is a draft strategy, EERE seeks stakeholder feedback through the corresponding request for information.

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1 Introduction

The focus of this strategic framework—and a key enabler for advancing toward a more circular economy—is addressing and overcoming the unique challenges related to recirculation of products and materials at the end-of-use (EOU) or end-of-life (EOL) back into the economy. Increasing product and material circularity positively affects decarbonization, environmental justice, and U.S. security of supply while also strengthening the U.S. manufacturing sector and fostering job creation. Increased product and material circularity is an essential ingredient needed to solve challenges that are top priorities for the Department of Energy's (DOE) Office of Energy Efficiency and Renewable Energy (EERE).

1.1 Goal of this Document

The overarching goal of this document is to provide a foundation of understanding of EERE's main objectives and key efforts in material and product circularity that will seed connection and collaboration with stakeholders across the U.S. government, industry, academia, and nonprofit organizations. Through this connection we hope to drive national-level impact through increased product and material circularity. To support this goal, this strategic framework will:

- Describe the potential economic and environmental impact of increasing product and material circularity.
- Communicate EERE's mission, vision, and objectives for increasing product and material circularity.
- Identify opportunities, challenges, and enablers for unlocking circularity.
- Highlight current and ongoing efforts related to product and material circularity in EERE.
- Communicate how EERE will continue to advance circularity in the future in partnership with other offices and agencies.

1.2 Linear Economy Concept

The current economic model, both in the United States and globally, is largely linear: resources are extracted, products are manufactured and used, and then discarded. This take-make-buy-use-waste linear economy model, illustrated in Figure 1, is material and energy intensive, relies on global supply chains that struggle to adapt following disruption, and favors single-use products that create substantial waste and environmental burdens.

In the last 50 years, material use has tripled globally and continues to grow at over 2.3% per year (United Nations Environment Program 2024). Most materials entering the economy are virgin materials, while estimates of the share of secondary materials declined from 9.1% in 2018 to 7.2% in 2023 (Circle Economy Foundation 2024).

Figure 1. Illustration of the ‘take-make-buy-use-waste’ linear economy

1.3 Circular Economy Concept

Acknowledging these increasingly problematic trends in material use, the concept of a circular economy has been proposed as an alternative to a linear economy. While there is no universally accepted definition of the circular economy, there is general agreement that it should strive to minimize resource extraction, waste generation, and environmental degradation and maximize the lifetime of products and materials circulating in the economy.

According to The Save our Seas 2.0 Act:

> “The term ‘circular economy’ means 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 used in such processes and activities to maintain their highest values for as long as possible; and (C) aim for the elimination of waste through the superior design of materials, products, and systems (including business models)” (U.S. Congress 2020).

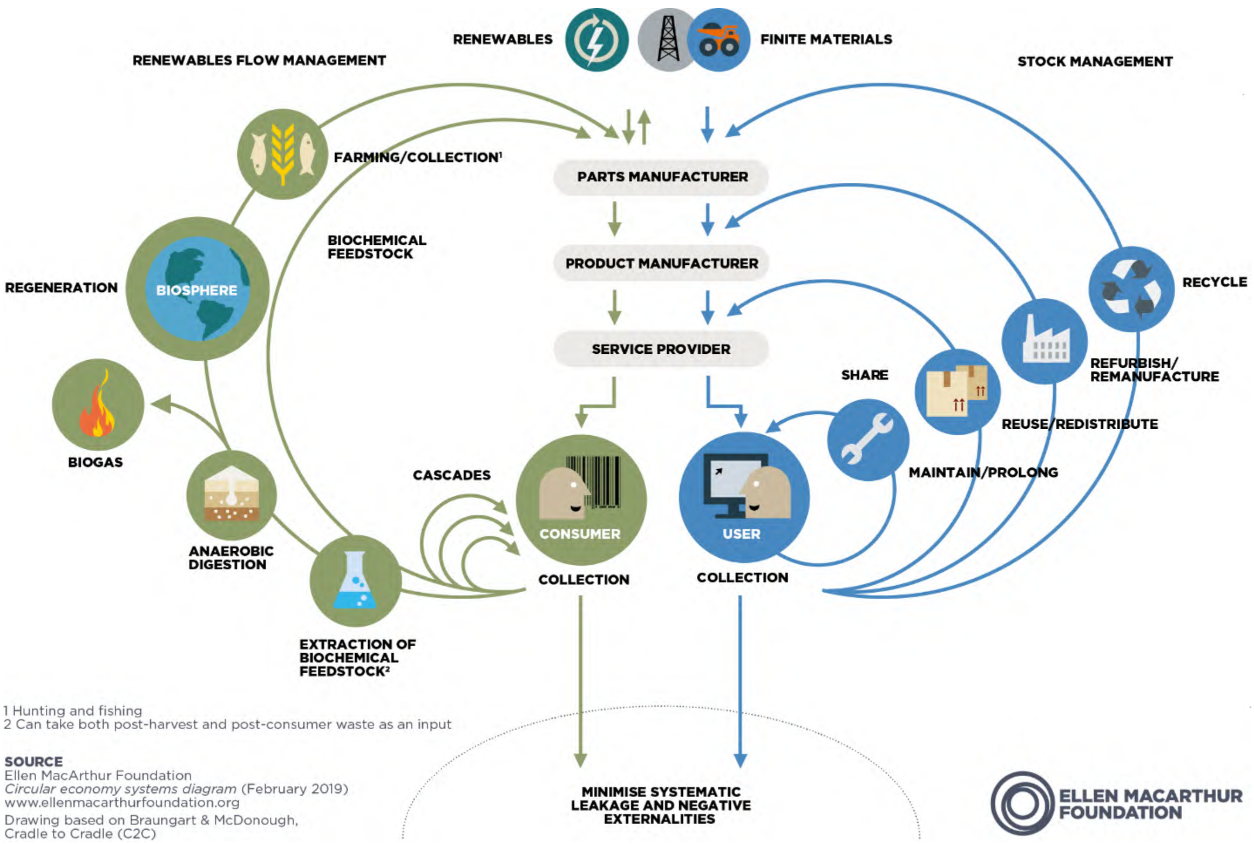
This definition draws strongly from the work of the Ellen MacArthur Foundation, which defines a circular economy as:

> “A systems solution framework that tackles global challenges like climate change, biodiversity loss, waste, and pollution. It is based on three principles, driven by design: eliminate waste and pollution, circulate products and materials (at their highest value), and regenerate nature” (Ellen MacArthur Foundation 2023).

The circular economy concept with circular pathways in both the ecological and technical spheres is illustrated in Figure 2.

The concept of a circular economy is broad and includes many potential contributing pathways both in the ecological and industrial spheres. DOE supports development in many of these areas including biomass utilization, carbon capture and utilization, waste reduction, increased efficiency, reduced material requirements via lightweight design or improved materials, and renewable energy generation (Bioenergy Technologies Office 2024, Office of Fossil Energy and Carbon Management 2024a, b; Better Buildings 2024;

Buildings Technologies Office 2024; Vehicle Technologies Office 2024; Office of Energy Efficiency and Renewable Energy 2024a).



1 Hunting and fishing
2 Can take both post-harvest and post-consumer waste as an input

SOURCE
Ellen MacArthur Foundation
Circular economy systems diagram (February 2019)
www.ellenmacarthurfoundation.org
Drawing based on Braungart & McDonough,
Cradle to Cradle (C2C)

Figure 2. Illustration of the circular economy concept showing both the biological cycle (left) and technical, or industrial, cycle (right). *Source: Ellen MacArthur Foundation, 2019*

1.4 Product and Material Circularity

While all aspects of the circular economy are important and can provide energy and environmental benefits, this strategy is more narrowly focused on product and material circularity. It is also worth noting that material efficiency and material circularity are also distinct. One can increase material efficiency through circularity, but there are many other pathways to improve material efficiency, including material substitution, manufacturing efficiency, and reducing the amount of material needed for an application.

What Is Product and Material Circularity?

Product and material circularity aims to minimize life cycle impacts though increasing recirculation of products and materials in the economy.

Focusing only on the industrial sphere (the right side of Figure 2), multiple strategies have been proposed and are summarized in Table 1. Collectively, these strategies that allow end-of-use (EOU) or end-of-life (EOL) products and materials to re-enter the economy are called Re-X pathways and include reuse, repair, refurbishment, remanufacturing, repurposing, and recycling (R3–R8 in Table 1). These pathways either extend a product lifetime (repair), enable multiple product lifetimes (reuse, refurbish, remanufacture, or repurpose), or recover materials at the EOL (recycle). Although we typically think of EOU and EOL as being after consumer use, these terms may also be applied to material waste generated in the manufacturing process or in business-to-business transactions that never reach the consumer. This EOU/EOL material is referred to in this document as post-industrial scrap and is often an ideal feedstock for circularity due to its purity and simple supply chain. Redesign strategies that facilitate or unlock reintroduction of products or materials back into the economy at the EOU or EOL are also part of the scope.

Some pathways (R0-R2: refuse, rethink, and reduce) deliver benefits related to reduced material consumption but do not necessarily address challenges associated with increasing recirculation of products and materials once they have entered the economy. While associated actions like increasing manufacturing efficiency, reducing production waste, or lightweighting components are important activities to reach our nation’s climate and clean energy goals, they do not inherently fit within the scope of this strategy as they do not impact how the product or material is handled at EOU or EOL stages. Likewise, incineration for energy recovery does not lead to recirculation of materials in the economy and is, therefore, not in the scope of this strategy.

For products and materials to recirculate in the economy, markets play a critical role, as illustrated in Figure 3. Business models and incentives must be aligned across the entire supply chain to ensure recirculation is economically viable. In addition to a technically feasible physical flow of goods, multiple market activities must take place for a circular pathway to be viable. If markets are not established or if incentives are not well aligned to promote utilizing them, the circular pathway will break down. A vivid example of the importance of markets in material circularity occurred when China implemented its Operation National Sword policy in 2018, leading to a collapse in the export market for recyclable materials and resulting in the halting or curtailing of some municipal recycling programs in the United States (Katz 2019).

Innovations to enable Re-X pathways must be both technically and economically feasible for all handoffs in the system. For example, remanufacture of an engine is only possible if, in addition to technical processes to restore the engine’s function, there are used goods markets to accept this input, component markets for the remanufactured engine, and a product market for equipment with the remanufactured part. The importance of these markets is critical to the success of the Re-X pathway and should be considered early in technology and supply chain development.

Table 1. Re-X Pathways[a]

	Re-X Strategy	**Description**	**Example**
	R0: Refuse	Make product redundant by abandoning function or by offering the same function with a radically different product.	Avoid production.
	R1: Rethink	Make product use more intensive (e.g., sharing models or multifunctional products).	Create X-as-a-service ownership models.
	R2: Reduce	Increase efficiency in product manufacture or use by using less energy or materials.	Reduce vehicle weight.
Product and Material Circularity	R3: Reuse	Reuse by another consumer of product that still fulfills original function.	Create a secondhand clothing marketplace.
	R4: Repair	Repair of defective product to be used with its original function.	Replace a faulty part in a car.
	R5: Refurbish	Restore an old product and bring it up to date.	Retread a tire.
	R6: Remanufacture	Use parts of discarded product in a new product with the same function.	Bring used engine back to original condition.
	R7: Repurpose	Use product or its parts in a new application or for a different function.	Give an electric vehicle battery a second life as grid storage.
	R8: Recycle	Process materials from discarded products into feedstocks for new products.	Use scrap as an alternative to virgin feedstock.

[a] Descriptions are adapted from Potting et al. (2016).

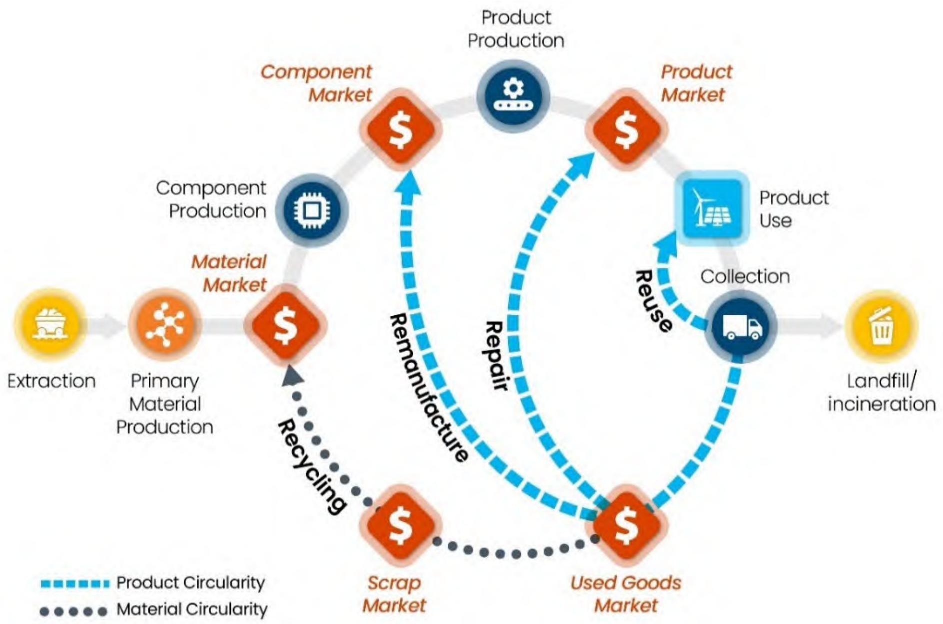


Figure 3. Conceptual illustration of some product and material circularity pathways emphasizing the role of markets in the circular economy

1.5 Key Considerations

To realize increased product and material circularity impacts across the entire life cycle, we must consider potential trade-offs, product lifetimes, material flows, and cascades to inform decision making. Such assessments are nontrivial, because there are multiple methods with different levels of granularity, temporal resolution, and data requirements (Walzberg et al. 2021).

1.5.1 Importance of Considering Multiple Impacts Across the Entire Life Cycle

Impacts across the entire life cycle of a product or material, including extraction of raw materials, manufacturing, transportation, product use, and EOL stages, need to be assessed to avoid unintended consequences. This cradle-to-grave analysis considers resources, energy, emissions, and wastes across the entire life cycle and is illustrated in Figure 4. To draw meaningful conclusions about relative impacts of different options, it is imperative that the boundaries used in the analyses are the same.

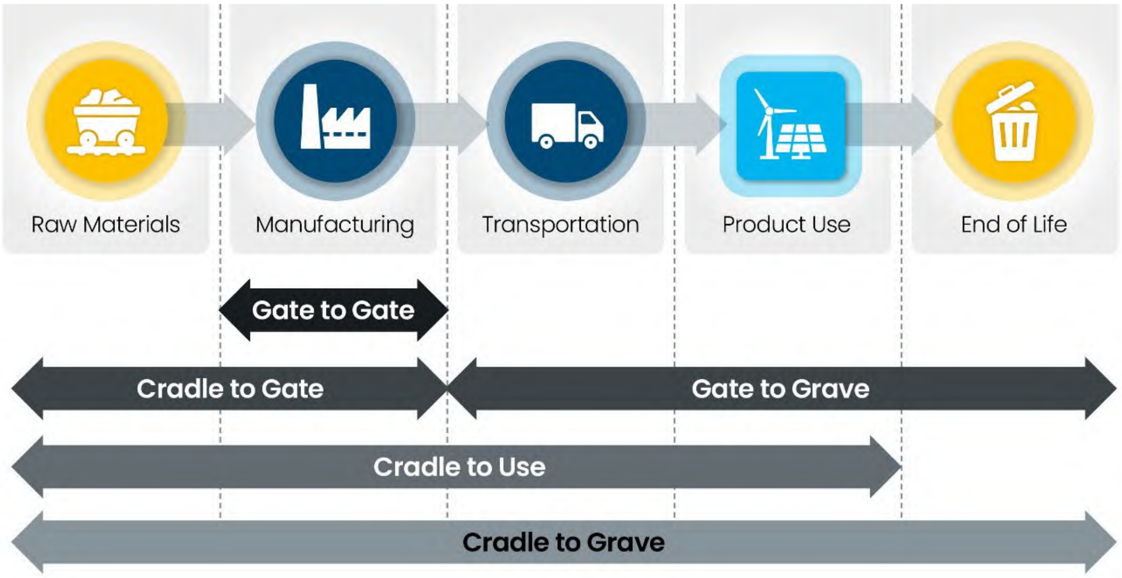


Figure 4. Illustration of different boundaries for studies that measure energy and environmental impacts of products. *Adapted from U.S. Department of Energy 2023c*

Key Concepts for Life Cycle Assessment

Life Cycle Assessment (LCA): A methodology for assessing the environmental impacts associated with the entire life cycle of a product or process (Industrial Efficiency and Decarbonization Office 2024).

Embodied Energy: The estimate of all the energy that is used to produce a material or product, including mining, manufacturing, and transportation.

Embodied Emissions: The estimate of the greenhouse gas emissions associated with production of a material or product, including mining, manufacturing, and transportation.

1.5.2 Impacts To Consider

Utilizing a holistic perspective is crucial when making decisions related to circularity. To understand the impacts and benefits across a product or material life cycle, there are multiple dimensions that can be considered to inform decision making. These dimensions can include economic, environmental, and social factors. Examples of these types of impacts are shown in Table 2. The ability to calculate quantitative metrics related to these impact categories will vary depending on the availability of data and models.

Table 2. Examples of Impacts To Consider When Assessing Impacts of Circularity

Economic	Environmental	Social
Cost of energy	Greenhouse gas emissions	Human health impacts
Cost of materials	Embodied carbon	Education opportunities
Employment	Energy use	Cultural preservation
Industry expansion	Waste generation	Rural development
Trade impacts	Biodiversity	Energy access
Energy imports	Water use and impacts	Energy security
Market demand	Air quality	Food security
Climate resilience	Land use impacts	Equitable distribution of impacts and benefits
Cost of waste management	Soil health	Impacts on specific groups and communities

1.5.3 Trade-Offs and Win-Wins

There are potential trade-offs when balancing impacts across an entire product life cycle. Minimizing greenhouse gas (GHG) emissions could result in increased water usage. Design choices to optimize material reduction may conflict with the ability to reuse or recycle the product.

Product design and material selection will be influenced depending on which EOL pathway is being optimized. Designing a product for reuse may require more material to ensure durability, resulting in higher initial embodied energy and emissions compared to a lighter-weight, single-use version. The more durable product may only reduce total impacts if enough reuse cycles are realized. Thus, reuse may only be preferable when there is a system and infrastructure in place to ensure the product is actually recovered and reused.

When considering if a product should be repaired or replaced, it is important to consider both the impacts of producing a new product as well as those related to the use of the product. For products whose use phase impacts are dominant, upgrading to a substantially more efficient product while recycling the old may be the best option. For products with most of their life cycle impacts in the cradle-to-gate phase, focusing on lifetime extension or enabling multiple uses is preferred.

Upgrading a product for increased efficiency during use represents a potential win-win, in that it both extends the product's lifetime and decreases use impacts. One example would be upgrading a building envelope to improve energy efficiency rather than constructing an entirely new building. However, if the upgrade is only cosmetic, replacement may be more beneficial because older buildings were designed to poorer energy efficiency standards (Hertwich et al. 2019).

1.5.4 Product Lifetime, Material Flows, and Cascades

In addition to impacts from different phases of product or material life cycle, the product use lifetime as well as overall material flows in the economy need to be considered.

The duration of product use varies tremendously, from minutes for some packaging, to a few years for a cell phone, to one or two decades for a car, to decades for buildings and infrastructure. These vastly different lifetimes result in different timescales at which EOU or EOL circularity benefits can be realized.

Several aspects related to product lifetime and material flows are worth considering, including:

- **Nominal versus actual lifetime.** The amount of time a product is used may vary substantially from the length for which it could be used or the length for which it was designed to be used. For example, repowering a wind site after fewer than 10 years leads to replacement of blades that would still nominally have had 20 years of service life left.
- **How quickly products circulate.** The time between manufacture and disposal of a product determines when the benefits of design for circularity can be realized.
- **Who bears the costs and who captures the benefits of redesign for circularity.** For example, designing a building for deconstruction and reuse may increase the costs and complexity during design and construction. However, the benefits of this circularity may not be realized for decades, and the building may change owners before then.
- **Shifting patterns of production and consumption.** Societal shifts can affect product and material flows. For example, cardboard for recycling was traditionally collected from industrial or commercial settings, but with the rise of ecommerce, more cardboard is ending up in homes where the recycling rate is lower (Paben 2022).
- **Rate of product and technology evolution.** For products where substantial technology evolution has occurred during their use, lifetime extension or multiple lifetimes may not be realistic options. For example, cathode ray tube televisions have no viable pathway for circularity other than recycling. Products or components that are relatively stable—such as steel I-beams or screws—have more viable Re-X pathways. Significant business model and incentive structure changes may be

required to reduce the rate of product evolution and reduce designed obsolescence.

- **Availability of secondary products and materials versus demand.** When demand for products or materials is increasing, secondary products or materials will not fully meet the demand due to the delay between manufacturing and the EOL. The exception is if material from EOL products with decreasing demand are recycled and diverted to the growing application. For emerging and scaling technologies, secondary materials will at first be available from manufacturing losses rather than EOL products.
- **Post-industrial versus post-consumer scrap availability.** Scrap generated during the production and manufacturing stage (new scrap) is available for recirculation almost immediately, while scrap from post-consumer products (old scrap) will only be available at the end of their use. Additionally, the purity and insight into the composition for post-industrial materials is generally higher than for post-consumer materials, which better facilitates recycling.

The flow of products and materials can be complex. A product could circulate in a closed loop, such as when a reusable cup is collected, washed, and reused for a different consumer or when an aluminum can is recycled back into a can. Alternatively, products or materials can circulate via open loops where they re-enter the economy in a different application. Glass from a bottle can be used as a secondary cementitious material in cement, for example, or a vehicle battery can be repurposed for stationary storage.

Because markets and technology are dynamic, closed loops are not always possible and may not always deliver optimal environmental outcomes. Overemphasizing closed loops may result in “unsustainable circularity,” where materials are retained in the economy but emissions increase (Rachal 2023; Allaway 2023). Relying on attributes such as “recycled” without a full analysis will not always yield optimal benefits (Vendries et al. 2020). Additionally, increasing circularity will not always reduce global demand for virgin materials. There may also be a rebound effect wherein circularity results in lower per unit impacts and costs, resulting in increased production and thus, greater total impacts (Zink 2017).

1.6 Potential for Increased Circularity

The large volume of waste generated each year in the United States represents a substantial opportunity to increase product and material circularity. Although there is limited data detailing all wastes, including industrial streams, the U.S. Environmental Protection Agency (EPA) estimates that 600 million tons of construction and demolition waste and 292 million tons of municipal solid waste (MSW) were generated in the United States in 2018 (U.S. Environmental Protection Agency 2020a).

Utilizing recycled materials is one option for keeping the value of these materials in the economy and may deliver substantial energy and emissions savings relative to producing goods from virgin materials. It is instructive to consider the amount of material from MSW being recycled, landfilled, or incinerated in the United States each year along with the embodied energy and approximate energy savings from using recycled rather than virgin materials. Examples for several commodity materials are shown in Table 3. The values shown are illustrative since exact energy and emissions savings for recycled materials will depend on supply chain aspects such as transportation distance and the technologies used to produce and process the materials.

Table 3. Waste Statistics for Some Commodity Materials in Municipal Solid Waste

Material	Embodied Energy (MJ/kg)	Millon Tons Recycled/Landfilled/ Incinerated	Energy Savings From Recycled Material[a]
Aluminum	210[b]	0.67 / 2.66 / 0.56[d]	95%[e]
Steel	26.5[b]	6.36 / 10.53 / 2.31[d]	60%–80%[f]
Glass	10.5[b]	3.06 / 7.55 / 1.64[d]	30%[g]
Paper and Cardboard	35[c]	45.97 / 17.22 / 4.2[d]	40%[g]
Plastics	100[b]	3.09 / 26.97 / 5.62[d]	33%[g]

[a] Estimated energy savings when using recycled materials rather than producing the material from virgin raw material.

[b] Milbrandt et al. 2022; [c] Milbrandt et al. 2024; [d] U.S. Environmental Protection Agency 2020a; [e] Raabe et al. 2022; [f] Reck et al. 2024; [g] U.S. Environmental Protection Agency 2016.

Estimates for the volume of materials entering landfills and for recycling rates can vary depending on the methodologies used. However, all estimates indicate a substantial potential for increasing material and product circularity. For plastic waste alone, it is estimated that in 2019 the United States spent $2.3 billion on landfilling plastics, which had an estimated market value of $7.2 billion and represented 3.4 embodied Joules of embodied energy—equivalent to 12% of the energy consumed by the U.S. industrial sector that year (Milbrandt et al. 2022). To get a picture of potential impacts of recycling on different materials and products, it is instructive to consider both current volumes and projected growth. Several of the fastest growing waste streams (plastics, textiles, and electronics scrap [e-scrap]) consist of materials with low recycling rates and high embodied energy, thus offering significant opportunities to reduce environmental impacts and retain economic value via increased circularity.

Post-industrial scrap and business to business recycling offers potential avenues for manufacturers to improve economics and drive efficiency. Unfortunately, there is little data publicly available that quantifies waste material generated in these processes, making it challenging to know the potential impacts of increasing their rates of recycling.

While recycling has a role to play in circularity, other Re-X pathways can potentially deliver larger reductions in demand for new materials and related emissions. An analysis of case studies estimates that remanufacturing can reduce new material requirements by between 80% and 98% and repair can save between 94% and 99% (United Nations Environment Program 2018).

Clearly, products entering landfills represent substantial market value and embodied energy. However, recirculating those products and materials back into the economy only makes economic and environmental sense when the processes and activities required to do so have lower costs and environmental impacts than new production and/or disposal. This requires functioning markets, as illustrated in Figure 3, as well as insight into the total life cycle impacts, as discussed in Section 1.5.1.

With the expansion of clean energy technologies—such as solar panels, wind turbines, fuel cells, and batteries—concerns related to both the EOL fate of these technologies, as well as the potential volumes and hazard of waste, have been raised and may slow deployment (Mirletz et al. 2023). Understanding the potential volume of EOL clean energy technologies in the context of other waste streams is important to inform decision making. For example, research indicates that by 2050, wind turbine blade waste in the United States could reach 370,000 tons per year (Electric Power Research Institute 2020). However, this is less than 0.15% of combined MSW and construction and demolition waste generated in the United States in 2018 (Wind Energy Technology Office 2023a).

With these emerging technologies, there is an opportunity to proactively include design that optimizes circularity to increase the domestic supply of critical materials, maximize clean energy production, and minimize life cycle impacts (Norgren, Carpenter, and Heath 2020). A 2022 critical review of the circular economy for lithium-ion batteries and photovoltaic modules recommended that research move from the prevailing emphasis on recycling technology development toward investigating other Re-X strategies more comprehensively (Heath et al. 2022).

1.7 Driving Impact via Increased Circularity

Not only is there ample opportunity for increasing product and material circularity, but doing so will have a variety of desirable economic, environmental, and social outcomes, as listed in Table 2. The White House report on U.S. innovation to meet 2050 climate goals identifies secure supply chains and circular economy innovation, which involves designing products and processes to increase recirculation of materials and products, as cross-cutting enablers for decarbonization (The White House 2022). Material circularity is seen as an essential component needed to solve the following challenges that are top priorities for DOE and EERE.

1.7.1 Decarbonization

Extraction and processing of material resources account for over 55% of GHG emissions, which climbs to over 60% if land mass use impacts are included (United Nations Environment Program 2024). From the mining and refining of raw materials to the assembly of finished products, manufacturing consumes considerable energy and generates significant emissions. In 2020, the U.S. industrial sector accounted for 33% of the nation's primary energy use and 30% of energy-related carbon dioxide (CO_2) emissions (U.S. Department of Energy 2022a).

The International Energy Agency (IEA) estimates that material efficiency could contribute up to 5% of economy-wide emissions reduction by 2040 (International Energy Agency 2020), with demand reduction from material efficiency contributing up to 30% of industrial decarbonization (International Resource Panel 2020). It plays a particularly important role in reducing emissions in the near term (up to 2040) while other measures such as the increase in clean energy usage and the implementation of novel manufacturing processes take longer. "Material efficiency" as defined by IEA includes more measures than only material circularity; however, this is a strong indicator of the important role that material efficiency will play in reaching 2050 emissions reduction targets.

Although the collection, transportation, cleaning, sorting, and reprocessing steps associated with various Re-X pathways have associated energy and emissions, they are often far less than what is associated with making new goods. Melting recycled aluminum scrap only uses 5% of the energy needed to produce primary aluminum, which translates to significant emissions savings (Raabe et al. 2022). More intensive product utilization via reuse, resale, or sharing business models can also deliver energy and emissions reductions via reduced demand for new production. For example, reusable utensils can deliver lower overall GHG emissions than single-use items when reused as little as just twice (Upstream 2021). Increasing the use life of clean energy technologies not only lowers their total life cycle impacts, but also increases the production of decarbonized electricity.

1.7.2 Community Benefits

Reducing energy and GHG emissions is important for meeting the nation's climate goals. However, there are other environmental and societal impacts that stem from the production and consumption of goods, including water scarcity and pollution, particulate and carcinogenic emissions, and environmental toxicity. The extraction and processing of materials contributes to 40% of particulate matter health impacts, with metals and non-metallic minerals processing being the highest contributors (United Nations Environment Program 2024). These and similar health impacts disproportionately affect disadvantaged communities that live and work near the extraction and processing sites. Increased circularity has the potential to benefit people and communities via improved health, prosperity, and resilience.

Waste handling processes like landfilling and incineration also contribute to environmental and social impacts, which are often felt more acutely by low-income communities who have been historically disadvantaged. With new waste streams, such as those that stem from the clean energy transition, there is an opportunity to develop circular pathways for those products and materials now before waste management issues and their associated impacts occur. Product and material circularity can also reduce environmental impacts by reducing raw material extraction and minimizing impacts associated with disposal.

Although increasing material circularity is often net positive as far as delivering environmental and social benefits, it is also important that we understand the impacts of increasing material circularity at the local community level. Understanding the impacts and benefits of increased circularity as it relates to communities is an emerging area of focus that EERE is starting to learn more about—and one that will inform the direction of future programs.

1.7.3 U.S. Security of Supply

With the rise of globalization, our supply chains have become increasingly complex and reliant on other countries for sourcing and processing materials. Supply chains that are highly dependent on very few sources, particularly foreign sources, are at risk of disruption. Limited supplies of certain materials that are essential for clean energy technologies, called critical materials, may inhibit our ability to achieve clean energy deployment goals. Increasing circularity of critical materials and the products they are in has been identified as one of the essential advancements needed to meet the demand for clean energy technologies and would reduce the cost of producing these materials by 30% (International Energy Agency 2024a).

Many critical materials require at least one processing step in a country where supply to the United States is at risk. DOE has identified the “electric 18” critical materials for energy that have moderate to severe supply chain risk in the near and mid-term (U.S. Department of Energy 2023a). Exporting products from the United States to other countries, often those with lower environmental standards, also means losing the opportunity to retain these materials in the U.S. economy by recycling, reuse, or repurposing. Improving circularity is one of the key pillars of DOE’s Critical Minerals and Materials Program because it eases domestic supply chain constraints (U.S. Department of Energy 2024d).

Taking EV batteries as an example, the lithium, cobalt, and nickel that are often components of batteries have high supply chain risk. Within the next 10 years, battery recycling could meet close to 80% of cobalt demand and almost 30% of nickel demand needed for battery manufacturing (The White House 2021). In addition, the use of recycled materials for battery manufacturing could reduce associated costs by 40%, energy use by 82%, water use by 77%, and SO_x emissions by 91% (Federal Consortium for Advanced Batteries 2021).

Extending product lifetimes and harvesting materials from EOL products reduces supply chain pressure by reducing demand and by increasing the supply of material available to the U.S. economy, leading to stronger, more resilient supply chains. These supply chain benefits occur for both critical materials and commodity materials.

1.7.4 Job Creation and Strengthening U.S. Manufacturing

Research estimates that the circular economy offers a $4.5 trillion economic opportunity globally by reducing waste, stimulating innovation, and creating employment (Lacy and Rutqvist 2015). The EPA estimates that in 2012 in the United States, recycling and reuse activities accounted for 681,000 jobs, $37.8 billion in wages, and $5.5 billion in tax revenues (U.S. Environmental Protection Agency 2020b). Recycling is estimated to create nine times more jobs than landfilling does while reuse creates 30 times more jobs (Eco-cycle n.d.). In 2011, the United States produced $43 billion of remanufactured goods, supporting at least 180,000 full-time jobs. Small- and medium-sized enterprises accounted for approximately 25% of this production (U.S. International Trade Commission 2012). Clearly, increasing product and material circularity represents an opportunity for capturing substantial economic benefits.

Creating circular supply chains in the United States strengthens the U.S. manufacturing ecosystem by expanding the manufacturing workforce and by creating better paying, higher-skilled, and safer jobs than traditional waste management. In addition to the direct benefits of job creation, increased product and material circularity can make U.S. manufactured products more competitive globally. In the last decade, there has been a rapid expansion of countries adopting or developing circular economy roadmaps and strategies (CircularEconomy.Earth 2020). The European Union, for example, has announced laws that require minimum amounts of recycled content in plastic packaging and is considering potential regulations for circularity in vehicle design (European Parliament 2024; Ragonnaud 2023). U.S.-based companies will need to comply with these emerging regulations to compete globally. Investing in innovations to advance product and material circularity is an opportunity for the United States to become a leader in developing and commercializing EOL processing technologies.

2 Product and Material Circularity Supports the Mission

Product and material circularity supports the DOE and EERE missions. It contributes to the deployment of clean energy technologies by expanding the supply of materials, lowering the impacts of the materials needed for clean energy technologies, and extending the lifetime of products to allow more clean energy generation with lower environmental, health, and societal impacts. Increasing material efficiency and circularity reduces energy demand related to raw materials and manufacturing processes, which contributes to economywide decarbonization.

Office of Energy Efficiency and Renewable Energy's Mission

EERE's mission is to accelerate the research, development, demonstration, and deployment of technologies and solutions to equitably transition America to net-zero GHG emissions economy-wide by no later than 2050, and ensure the clean energy economy benefits all Americans, creating good paying jobs for the American people - especially workers and communities impacted by the energy transition and those historically underserved by the energy system and overburdened by pollution (Office of Energy Efficiency and Renewable Energy 2024b).

2.1 Vision, Mission, and Objectives for Increasing Product and Material Circularity

2.1.1 Vision

The United States is a leader in sustainable economic growth by ensuring materials and products remain in circulation to minimize environmental impacts and raw material consumption while simultaneously maximizing quality of life and environmental justice.

2.1.2 Mission

The mission of EERE's work in this area is to develop, demonstrate, and deploy technologies and approaches needed to increase product and material circularity.

2.1.3 Objectives

As described in Section 1.7, increasing circularity directly contributes to decarbonization, community benefits, U.S. security of supply, and job creation and strengthens the U.S. manufacturing sector, all important aspects of EERE's mission.

2.2 Framework for Prioritizing Research and Development

The economy is made up of countless products composed of a nearly infinite variety of materials. The various approaches to increasing circularity of these products and materials is similarly complex. To prioritize where to focus finite research and development resources, we propose a framework for how EERE prioritizes investment to drive real world impacts.

This framework includes a three-step approach comprised of:

- Assessing the potential impacts of increasing circularity for a product or material.

- Identifying the transformation pathway and the barriers to deployment.
- Considering the timeline for deployment and scaling.

2.2.1 Assessing Potential Impacts

The first step of the process is to assess potential for impact. As mentioned in Section 1.7, EERE aims to achieve multiple impacts, including emissions reduction, community benefits, security of supply, and U.S. manufacturing competitiveness. Impacts should be assessed independently, allowing for reprioritization depending on the relative importance of each.

For example, to determine which materials should be prioritized for developing new circular technologies consider three hypothetical materials with illustrative data provided in Table 4. To accurately estimate the potential emissions savings by increased recycling, we need data related to the amount of material not currently recycled and the carbon intensity of primary and recycled material production. Within these hypothetical materials, Material C has the largest potential for emissions reduction via recycling due to the high volume of material not currently recycled. Despite the large reduction in emissions intensity for recycled Material A, it has lower potential emissions savings due to the high current recycling rate. Thus, if emissions reduction is the primary driver, Materials B and C have the highest potential emissions reduction based on the volumes of potential material for recycling and the emissions saved by recycling rather than making new materials and should be prioritized.

Within that subset, we might next consider the recycled material market size or projected market growth to understand the potential impact on manufacturing competitiveness and/or which markets are more likely to deploy novel technologies in the near term. Material C should be prioritized due to the large potential emissions reduction with increased recycling and the high growth rate, although market development activities for recycled material may be needed. Energy savings and material not currently recycled, like the data found in Table 3 can provide indicators for which materials should be prioritized; however, more data is needed to develop accurate figures for potential emissions savings. This includes the need for this data at the industry level (e.g. aluminum) as well as more granular data that tracks specific material flows (e.g. grades and alloys of aluminum across multiple industries). This data spans multiple industries and complex supply chains; coordination across ecosystems is critical to obtaining the data needed to perform the calculations illustrated in Table 4.

Table 4: Example of How Material-Specific Data Can Inform Investment Prioritization

Material	Amount Landfilled and Incinerated (Millon ton)	CO_2 Intensity Primary Material (ton CO_2eq /ton)	CO_2 Intensity Recycled Material (ton CO_2eq /ton)	Potential Emissions Savings by Increased Recycling (Million tons CO_2eq)	Recycling Rate (%)	Recycled Material Global Market Size (Billion US$)	Global Annual Market Growth (%)
A	1	15	1	14	60	5	10
B	10	5	2	30	80	10	3
C	25	2	1	50	15	3	10

The following questions and aspects should be considered when determining how to prioritize investments in circularity technologies.

Decarbonization potential can be quantified taking the following considerations into account:

- What volume of material can be addressed by additional circularity measures compared to what is already practiced and based on the distribution of products?
- What is the projected growth of production and consumption?

Community benefits encompass several impacts, some of which can be difficult to quantify but should include consideration of:

- How will the number, quality, and location of jobs be affected by shifting to a circular supply chain?
- What are the environmental and health impacts (beyond emissions) of the production of virgin materials and how will those change by employing circular technologies?
- What environmental and health impacts are caused by landfilled and discarded products and materials and what mitigation would come through circular supply chains?

Security of supply potential can be assessed by considering:

- Is this a critical material for which supply chain challenges have been identified?
- To what extent can circularity address a current vulnerability of the domestic supply chain? This can be informed by informed by existing federal assessments and analysis such as the Critical Materials Assessment (U.S. Department of Energy 2023a).

- How do different Re-X pathways impact those vulnerabilities?

U.S. manufacturing competitiveness impacts evaluation should include consideration of:

- What is the international and domestic policy landscape affecting the product or material?
- Is there a potential for a “green premium” in the domestic and global markets?
- Can the U.S. take a leadership position in commercializing EOL processing technologies?

2.2.2 Identifying the Transformation Pathways and Barriers

For technologies with high impact potential, the next step is identifying likely transformation pathways to reach commercialization. In doing so, barriers to adoption will be discovered and can generally be classified as technical, economic, or policy in nature. Classifying barriers helps inform the likelihood that EERE can affect change in a given technology space, and it guides the type of work needed to support adoption. For technical barriers, funding programs can be designed to identify and advance potential solutions that overcome these barriers. In many cases, technology advancement can also be used to improve the economics for a given technology or process. EERE also plays a role in addressing policy barriers by conducting analysis and providing high quality tools and data to be able to quantify the impacts of technology deployment compared to the status quo, which can drive the intended impacts of policy levers. An illustration of this role is working across agencies to populate the Federal Lifecycle Commons with high quality data needed to support the Federal Buy Clean Initiative, which incentivizes procurement of construction materials with low embodied carbon, including recycled materials. The role of EERE might involve developing methodologies to assess embodied energy and emissions of products and materials that involve multiple uses via Re-X pathways.

Questions to be considered while assessing the transformation pathways include:

- What technological advancements are needed and how do they impact economic viability?
- What is the policy landscape and what data or tools are missing to inform policy? What policies will be most effective at aligning incentives to drive adoption and deployment?
- How might the barriers evolve over time?
- What business model adaption is needed to make circular supply chains economically viable?

2.2.3 Considering Timeline for Deployment and Scaling

Finally, factors impacting the pace and scale of deployment should be considered. Applications that have the potential for more rapid deployment and larger scalability should be prioritized. Mature markets may be slower to adopt new technologies than emerging ones where design choices and manufacturing supply chains are still flexible. Products such as electric vehicles or solar cells that have large potential to scale and technology that is evolving should be prioritized over niche, mature products. Important aspects to consider here are:

- What markets and/or products are poised for rapid adoption of this technology?
- What potential products are well-positioned for growth in demand in the near future?
- Are innovation and technology advancements likely to diffuse to other products or supply chains and what factors will influence diffusion?
- What infrastructure expansion is needed?

2.3 Importance of Advancing Office Missions

EERE has 10 technology offices, each with their own mission and objectives that support EERE's broader mission. In addition to the technology offices, EERE Office of Strategic Analysis (SA) is part of the Integrated Strategies Offices and also manages a variety of projects related to circularity. The importance of increasing product and material circularity as it relates to relevant EERE office missions is described in the following section.

2.3.1 Importance of Product and Material Circularity to Office Missions

2.3.1.1 Advanced Materials and Manufacturing Technologies Office

The Advanced Materials and Manufacturing Technologies Office (AMMTO) makes strategic investments to advance the material supply chains and product life cycles that support a robust manufacturing sector, supply chain security, environmental sustainability, and economy-wide decarbonization. Material circularity is essential to meeting these objectives and is a cornerstone of the Secure and Sustainable Materials Program within AMMTO. This program funds the development of innovative technologies that include material and product design for circularity, process development, and addressing supply chain challenges for recycling, remanufacturing, reuse, and other Re-X pathways.

2.3.1.2 Bioenergy Technologies Office

The Bioenergy Technologies Office's (BETO's) priority is a renewable and circular carbon economy. BETO enables a circular carbon economy by focusing on increasing efficient use and recovery of carbon-rich feedstocks to produce biofuels and bioproducts, including plastics made from bio-based feedstocks. The main areas of focus are: (1) feedstock supply and logistics, including algae and municipal solid waste; (2) converting bio-based carbon into fuels and chemicals; and (3) demonstrating processes and addressing market barriers.

2.3.1.3 Building Technologies Office

The Building Technologies Office's (BTO's) work has historically revolved around energy efficiency and reducing operational emissions. That focus, however, is slowly expanding. With the publication of the Buildings Blueprint, minimizing embodied life cycle emissions has been identified as one of the key objectives for the building sector (U.S. Department of Energy 2024a). This objective will be an important focus area for BTO in the future.

2.3.1.4 Geothermal Technologies Office

The Geothermal Technologies Office (GTO) mission is to increase geothermal energy deployment through research, development, and demonstration of innovative technologies across geothermal power development, direct-use applications, and geothermal heat pumps. Given the limited opportunities to implement circularity strategies on permanently installed subsurface infrastructure, GTO seeks to minimize life cycle environmental impacts and to create recycling pathways for applicable parts of geothermal operations. Examples of GTO activities include increasing the sustainability of cement for high-temperature downhole environments, lithium recycling, recirculation of geothermal fluids, and repurposing of existing infrastructure for geothermal energy systems.

2.3.1.5 Hydrogen and Fuel Cell Technologies Office

The Hydrogen and Fuel Cell Technologies Office (HFTO) is dedicated to investing in hydrogen's circular economy. Through collaborations with researchers, the office's efforts explore work to sustainably design, recover, reuse, and recycle materials used in hydrogen fuel cells and electrolyzers, including platinum group metals (PGMs) and perfluorosulfonic acid (PFSA) membranes. These investments ensure supply chain security and promote hydrogen technology manufacturing and national decarbonization.

2.3.1.6 Industrial Efficiency and Decarbonization Office

Increasing material circularity supports the Industrial Efficiency and Decarbonization Office's (IEDO's) mission to accelerate the innovation and adoption of cost-effective technologies that eliminate industrial GHG emissions. EOL materials like scrap steel and recycled plastics are one of several manufacturing feedstocks that support emission reduction in the industrial sector.

2.3.1.7 Solar Energy Technologies Office

The Solar Energy Technologies Office (SETO) is focused on strengthening domestic supply chains and reducing critical material usage through both minimizing the critical materials contained in solar modules and extending the modules' operational lifetime. SETO is also investing in technologies that enable a circular economy for photovoltaics by recovering high value and critical materials from decommissioned solar modules.

2.3.1.8 Vehicle Technologies Office

The Vehicle Technologies Office (VTO) provides low cost, secure, and clean energy technologies to move people and goods across America. VTO focuses on reducing the cost and improving the performance of vehicle technologies that can reduce petroleum dependency. The VTO materials team works closely with the Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability (U.S. DRIVE) Partnership to enable vehicle lightweighting of structures and systems, application of sustainable automotive materials, and reduced dependence on critical materials.

2.3.1.9 Wind Energy Technologies Office

The Wind Energy Technologies Office (WETO) is working with researchers across industry, academia, and national laboratories to create a circular economy for wind energy. Extending the life cycle, reducing waste, and enhancing the recycling of wind turbine materials are important strategies to promote sustainability and reduce the environmental impact of wind energy systems. These approaches help minimize waste, conserve resources, and reduce GHG emissions associated with the production and disposal of wind turbine components.

2.3.1.10 Water Power Technologies Office

The mission of the Water Power Technologies Office (WPTO) is to enable research, development, and testing of new technologies to advance marine energy as well as next-generation hydropower and pumped storage systems for a flexible, reliable grid. There is little new hydropower capacity being added to the grid, so this program's circularity efforts involve lifetime extension to maximize utilization of components. WPTO released a strategy that identifies research and development priorities in advanced manufacturing and materials for the hydropower sector (U.S. Department of Energy Water Power Technologies Office 2024). Marine energy devices are primarily at the predeployment and early deployment phases, where recyclability of materials at EOL is incorporated into design. Evaluation of material recyclability and reuse potential after extended exposure to marine conditions is an area of research for the office.

2.3.2 Strategic Analysis

EERE's Office of Strategic Analysis (SA) supports the development of foundational circularity analytical methods and their application in cross-cutting analysis of the role of circularity in EERE mission spaces. SA also serves in a coordinating role for inter-office and interagency efforts related to circularity analysis and strategy.

3 Opportunities, Challenges, and Enablers

The purpose of this section is to highlight significant opportunities to implement Re-X supply chains and technologies, implementation challenges to be overcome, and enablers for realizing opportunities to increase product and material circularity. First, specific interventions that enable product lifetime extension or recovery of materials at EOL are discussed, followed by cross-cutting technologies that may impact multiple Re-X pathways. The examples provided are not exhaustive, but instead serve to illustrate opportunities, challenges, and enablers related to different pathways and technologies. Finally, key nontechnical challenges and enablers are highlighted since increasing circularity is not only limited by technical aspects but will also require policies that support incentive alignment and business model evolution. More detailed discussion of specific technology and material areas of focus for EERE will be covered in Section 4.

3.1 Re-X Pathway Specific Opportunities, Challenges, and Enablers

Several pathways can enable lifetime extension of products and materials via interventions that either extend the lifetime or those that enable multiple lifetimes.

3.1.1 Redesign to Unlock Circularity

Incorporating EOU or EOL considerations at the design stage of both product and business model development is critical to achieving product and material circularity. These considerations help align incentives across the product life cycle as well as reduce the technical challenges associated with repair, remanufacturing, and recycling. Illustrative examples are given in the following.

Opportunities include:

- Designing materials to eliminate problematic contaminants and/or facilitate recycling.
- Designing for disassembly to reduce complexity and contamination that can hinder repair, remanufacturing, and recycling of materials and products.
- Selecting materials and optimizing design to increase recyclability and reduce contamination. For example, using debondable adhesives and fastener materials that do not substantially contaminate recycling streams, harmonizing aluminum alloy specification to increase recyclability, and eliminating problematic additives to reduce contamination in recycled plastics.
- Ensuring access to software and controls system for product use life extension. As more products are digitized, software access may become the limiting factor for useful life. For example, some computers can become inoperable due to software expiration, despite having fully functional components.

Challenges include:

- Costs of redesign and material qualification.
- Lack of workforce well versed in design for disassembly.
- Misalignment of incentives and costs across the value chain, including the incentives/costs for design and material changes and changes to durability.
- Software licensing and cybersecurity concerns that may hamper software and control system access.

Enablers include:

- Automated sorting and disassembly capabilities.
- Workforce training in design for circularity and increased awareness of material selection for improved recyclability.
- Development of debondable adhesives, novel separation, and use of fastener materials that do not substantially contaminate recycling streams.
- Integration of software and control interoperability in addition to mechanical aspects in product and business model design for circularity.

3.1.2 Reuse

Reusing products for their original purpose can reduce the demand to produce new ones as well as the burdens related to disposal. However, successful reuse supply chain development requires not only technical innovations, but also business model innovation and standards development. Illustrative examples are given in the following.

Opportunities include:

- Replacing single-use items for food service and packing with reusable and refillable products.
- Reusing clean energy products that are decommissioned due to repowering but still have substantial use life remaining.
- Recovering and reusing high value, high embodied energy and supply chain disruption sensitive parts and components, such as integrated circuits, power electronics, motors, and permanent magnets.
- Reuse of building materials that result from cosmetic renovations but retain suitable performance.

Challenges include:

- Lack of collection and sanitization infrastructure limits the ability to economically scale reuse of food service items and packaging.
- Need for safety, reliability, consumer acceptance, and economic viability for reuse of clean energy technologies. For example, the cost of PV modules is only ~10-30% of the installed system costs, meaning second-life panels do not dramatically lower overall costs (Ramasamy et al. 2023).
- Need to collect, identify, assess fitness for reuse, and redistribute products economically via functional marketplaces.
- Highly dispersed nature of materials recovered from renovations and limited number of products with same appearance.

Enablers include:

- Standards to support reuse from design to collection and sanitization are needed to allow systems to scale and utilize shared infrastructure.
- Tracking of product history combined with improved labeling.
- Optimizing reverse logistics systems to minimize impacts and costs associated with transportation.
- Facilitating uniform safety and evaluation practices for second use products via appropriate standards and best practices.
- Automated product recognition systems, standardization of component design, and development of assessment methodologies.
- Remanufacturing approaches to yield consistent cosmetic appearance from recovered products with different styling.

Enabling Circularity for Solar Power

SETO released the Materials, Operation, and Recycling of Photovoltaics (MORE PV) Funding Opportunity Announcement in 2023. Topic 2 of the MORE PV Funding Opportunity Announcement (FOA) requested applications for a multi-institute partnership that would address challenges associated with Re-X pathways for PV panels. The FOA called for diverse teams to optimize performance, cost, and environmental impact to support a terawatt of PV deployment.

Developing efficient and balanced methods to process decommissioned PV systems using Re-X concepts requires collaboration among multiple stakeholder populations. Some stakeholders, such as recyclers or government offices, are not familiar with EERE or SETO programs. The MORE PV FOA addresses these needs by setting up a Solar Partnership to Advance Recycling and a Circular Economy (Solar PARC) dedicated to improving materials recovery efficiency and developing safe EOL practices for solar modules and other PV system components by establishing a database on current and historical state of EOL volumes and handling for PV EOL materials. The FOA requested partnerships among researchers, manufacturers, asset owners (waste generators), recyclers, and government entities. The major activity of the Solar PARC would be technical research to develop processes to recover materials from decommissioned PV system components to optimize environmental impact and benefit domestic supply chains. Other major activities include stakeholder workshops to share information on developments in Re-X for PV and to gather data relevant to Re-X to inform and optimize approaches for EOL PV.

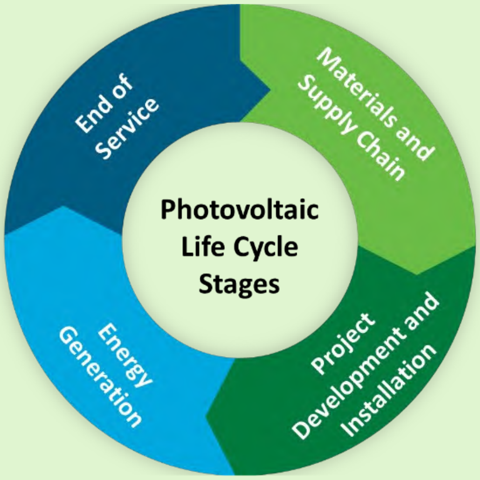


Figure 5. Life cycle stages of a photovoltaic power plant

3.1.3 Repair/Refurbishment/Remanufacturing

The manufacturing process dominates the life cycle impacts of many products due to the energy and material inputs required. Therefore, extending the useful life of a product—through interventions such as monitoring, preventative maintenance, and repairs—can yield substantial benefits. Additional product lifetime can be achieved via refurbishment or remanufacturing to meet or exceed initial product performance. Remanufacturing can not only reduce demand for raw materials, but it can also lower total cost of ownership and relieve supply chain pressure for critical components. Retrofitting is an opportunity to extend the lifetime of a building while improving its efficiency, thereby reducing use phase impacts. Illustrative examples are given in the following.

Opportunities include:

- Actively monitoring for proactive maintenance and repair. For example, extending a wind turbine blade's life by five or 10 years is estimated to reduce life cycle impacts by 24% to 48% (Liu, Meng, and Barlow 2019).
- Remanufacturing highly engineered, high embodied energy components, such as engines and wind turbine gear boxes.

- Retrofitting existing buildings to increase performance and extend lifetime rather than requiring demolition and new construction. Adaptive reuse of an existing office building for apartments may reduce emissions by 34 to 48% and require 72% less material compared to constructing a new building (Gursel, Shehabi, and Horvath 2023).
- Refurbishing consumer goods, such as office furniture, to enable retention of key components while updating the style to meet changing consumer preferences.

Challenges include:

- Cost of in-field monitoring and repairs as well as access to skilled workforce.
- Customer perception that remanufactured goods may be less reliable or of lower quality and business perception of increased complexity of remanufacturing business model.
- Uncertainty around costs of adaptive reuse.
- Difficulties complying with codes and standards, working around existing building design, and comparing differences in material circularity and life cycle impacts for on-site versus off-site construction and retrofits.
- Need for cost-effective collection and transport of bulky or heavy products.

Enablers include:

- Drones, computer vision, artificial intelligence, machine learning, and digital twins leveraged for active monitoring. In-field repair approaches and material and design choices to facilitate repair.
- Advanced manufacturing techniques such as additive and hybrid manufacturing. Warranties and outreach to increase customer confidence.
- Case studies and tools that quantify benefits of adaptive reuse and waste minimization. Implementation of codes and zoning provisions at the local level specifically for adaptive reuse.
- Cost-effective approaches to refurbish items to consistent, modern appearance and the development of a workforce with necessary skills for refurbishment.

Automated, In-field Wind Turbine Blade Inspection

Wind turbine blades are the largest single-piece composite structures in the world, with some now exceeding the length of a football field. They undergo hundreds of millions of fatigue cycles during their lifetimes and are often located in remote areas. Ensuring the reliability of these skyscraper-sized structures over their lifetimes is a difficult challenge—wind turbine blades cannot be sent to a hangar for maintenance in the same way that airplanes can. The WETO-funded, Sandia National Laboratories-led Blade Reliability Collaborative seeks to understand the root causes of premature blade failure and unplanned maintenance and to determine the most cost-effective methods of ensuring that blades can survive their expected operational life.

An example of innovation for in-field inspection to extend blade lifetime by detecting damage early and allowing for repair is Sandia National Laboratories' Assessment Robot for Resilient Optimized Wind energy (ARROW$^{(e)}$). Through innovations in robotics, ARROW$^{(e)}$ brings automated, high-tech wind blade inspections to the field that can detect deep, subsurface damage at low cost.

Figure 6. Photo of ARROW$^{(e)}$. *Photo from Sandia National Laboratories*

Advanced Manufacturing Technologies for Repair, Remanufacturing, and Repurposing

Advanced manufacturing techniques, such as additive manufacturing[1] and hybrid manufacturing,[2] have potential to expand repair and remanufacturing (Fillingim and Feldhausen 2023). A 2017 remanufacturing roadmap identified that the development of more cost-effective additive manufacturing processes could drive their adoption by small- and medium-sized remanufacturing companies (Rochester Institute of Technology 2017).

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[1] Additive manufacturing, or 3D printing, is the construction of three-dimensional objects from a digital model. Objects can be manufactured by depositing, joining, or solidifying materials together, typically layer by layer.

[2] Hybrid manufacturing is a combination of additive and subtractive manufacturing capabilities in one system.

Hybrid manufacturing expands possibilities for repair of nonplanar parts by leveraging the five-axis mill to prepare the substrate for deposition (Feldhausen et al. 2022). It can also increase the U.S. tool and die industry's rapid reconfiguration capabilities in the face of supply chain shocks such as the COVID-19 pandemic by enabling rapid repurposing of existing tooling (Saleeby et al. 2020). The AMMTO-supported Manufacturing Demonstration Facility (MDF) at Oak Ridge National Laboratory is developing hybrid manufacturing technologies including the co-development and installation of the world's largest metal hybrid additive manufacturing system.

3.1.4 Repurposing

Product cascades, where a product or part that has reached the end of use in one application is repurposed for another application, can bring benefits by retaining materials and value in the economy. Supply chains based on repurposing can be complex because the supply of products available for the second life are dependent on the dynamics in the first use application. Illustrative examples are given in the following.

Opportunities include:

- Using repurposed EV batteries for stationary energy storage. Utilizing EV batteries for storage of solar energy in homes may reduce GHG emissions by 58% compared to the use of a new lithium-ion battery (U.S. Department of Energy 2022a).
- Repurposing composites for structural applications. Using composites from wind turbine blades as transmission line poles has been demonstrated, and analysis suggests that it could be cheaper than using steel poles while producing lower GHG emissions than other EOL options for the blades (Henao et al. 2024).

Challenges include:

- Costs and safety risks associated with battery transport. Determining battery suitability for second life applications.
- Decommissioning, sectioning into desired sizes, and transporting composites from turbines economically and without damage.
- Confidence in and adoption of repurposed composites by designers of structural applications.

Enablers include:

- Technologies to rapidly assess battery health, as well as approaches to increase safety during transportation and reduce associated costs.
- Incorporation of second-life considerations into EV battery design.

- Onsite approaches to recover undamaged and appropriately sized components for easier transport.
- Insight into volume and design of parts available for reuse as well as applications where they could be repurposed.

Building Circular Electric Vehicle Battery Supply Chains

EV batteries illustrate the complexity of building circular supply chains. There are multiple intervention points along the battery lifecycle for increasing circularity, including design choices, material selection, and repairs to extend first use life in vehicles. Once the battery reaches its EOL for EVs, it can be routed for repurposing for energy storage or routed for recycling. In addition to technical challenges for different Re-X supply chains, the business models and financing must also support recirculation.

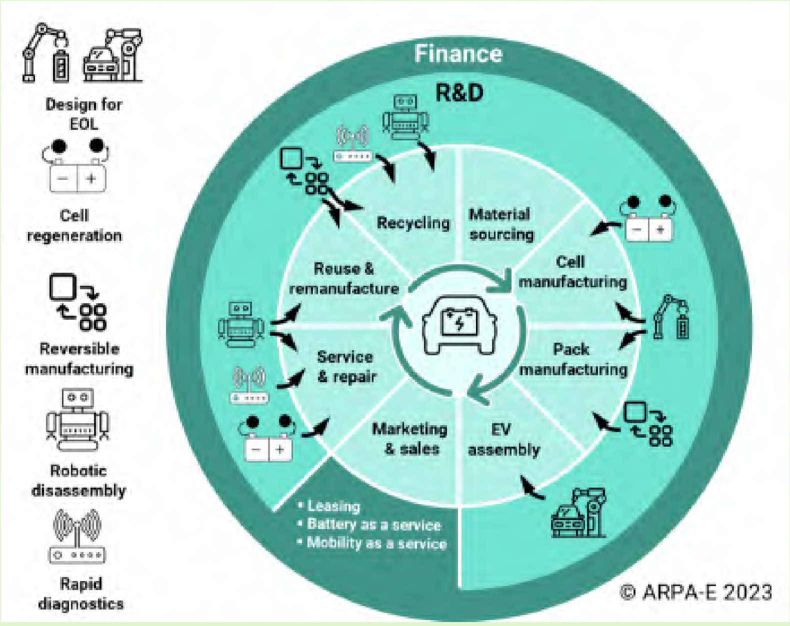

Figure 7. (Right) Illustration of strategies that can be deployed along a circular EV battery supply chain. *Source: U.S. Department of Energy Advanced Research Projects Agency – Energy 2024*

3.1.5 Recycling

Recovering materials from EOL products can reduce demand for virgin feedstocks and decrease impacts associated with landfilling or incineration. While extending product lifetime may result in lower impacts and higher retention of value, there will always be a need for material recovery when products reach their ultimate EOL either due to unrecoverable loss of function or obsolescence. Additionally, because scrap production during manufacturing cannot be completely eliminated, it can serve as an input for recycling. For emerging technologies, scrap generated during manufacturing may initially dominate recycling streams. Illustrative examples are given in the following.

Opportunities include:

- Increasing recycling rates of commodity materials from MSW (see also Table 3) and other waste streams such as construction and demolition debris and post-industrial streams.
- Recycling electronic scrap (e-scrap) to increase domestic production and U.S. security of supply of critical materials such as rare earth elements (REEs) and PGMs.
- Automated disassembly and/or improved sortation of complex waste streams such as automotive shredded waste to reduce contamination of feedstocks for recycling.
- Utilizing recovered materials as feedstocks in manufacturing, including in product and material cascades where materials are utilized for new areas. For example, using post-consumer glass in concrete or using carbon fibers recovered from continuous composites for short fiber composites.

Challenges including:

- Collection and transportation for low value, low density materials, such as flexible plastics, wood, insulation, and drywall materials.
- High contamination levels in post-consumer material streams.
- Low concentration of critical materials in e-scrap streams.
- Separating critical materials economically.
- Cost of processing and separation versus bulk disposal.
- Variable quality, contamination levels, and/or lower performance or higher costs of recycled materials relative to virgin materials.
- Cost to validate secondary feedstocks and confidence in safety and security of supply.

Enablers includes:

- Advanced sorting leveraging artificial intelligence, machine learning, and advanced robotics to increase recovery and improve purity of material streams for recycling.
- Harmonization of composition and design to improve recycling and reduce waste (e.g. prefabricated construction).
- Improved recycling technologies that are more robust against contamination. Increased access to recycling and collection for rural areas and multifamily units.
- Approaches that integrate PGM or REE recovery into existing recycling processes.
- Production of high value co-product generation to improve critical materials recycling economics.

- Technologies that reduce energy, water, and waste generation for critical materials recycling.
- Rapid characterization techniques.
- Smart manufacturing and adaptive processing that can compensate for more variable feedstocks.
- Clearing houses to match available recycled materials with application feedstock requirements.

Critical Materials Innovation Hub is Advancing Technologies for Critical Materials Recovery from E-Scrap

The Critical Materials Innovation (CMI) Hub has successfully developed multiple technologies to improve recovery of critical materials from e-scrap. Examples of technologies that have secured follow-on funding include:

Acid-Free Dissolution Recycling (ADR): The ADR process is highly selective for recovering REEs in preconcentrated magnets, as well as magnets in dilute waste streams. This high selectivity differentiates the ADR technology from other approaches and demonstrates its robustness. Ames National Laboratory collaborated with the company TdVib, LLC, to scale up the recycling process without any acids and to limit the generation of waste, making for a more environmentally friendly process. ADR also removes the need for pre-heating, which sets it apart from other recycling processes used to demagnetize REE magnets. Collaborative efforts are underway to produce 3–5 tons of rare earth oxide, which is a crucial part of the REE magnet supply chain for clean energy technologies, such as electric motor vehicles, or even consumer electronics like hard disk drives (Advanced Materials and Manufacturing Technologies Office 2023).

Membrane Solvent Extraction (MSX): MSX is a highly selective, energy efficient, cost-effective, and environmentally friendly process that recovers critical materials from recycling streams and other sources. By combining hollow fiber membranes, organic solvents, and tailored extractants, only the metal ions of interest can pass through the membrane, yielding high selectivity. MSX has been successfully applied to recover REEs and battery critical materials, with the added benefit of being able to separate light and heavy REEs and battery critical materials from one another. A range of elements from magnets, batteries, and other devices can be recovered in a facility equipped for MSX (Staff Writer 2020).

Innovations to Overcome Contamination in Recycled Aluminum

The ability to produce high-performance aluminum alloys from post-consumer scrap is limited due to contamination from ferrous materials. The current practice is to dilute scrap with primary aluminum, resulting in an increase in energy use, emissions, and cost (Whalen et al. 2023a). Supported by multiple EERE offices, the Pacific Northwest National Laboratory developed a new way to manufacture high-performance aluminum alloy tubing with lower embedded energy and improved mechanical properties. The Shear Assisted Processing and Extrusion (ShAPE™) process not only reduces the energy needed to process metals, but also improves the mechanical performance via refining the microstructure as illustrated in Figure 9 (Advanced Materials and Manufacturing Technologies Office 2022). This manufacturing innovation has the potential for 100% scrap usage without needing dilution to reduce impurity levels, resulting in the potential to reduce the life cycle carbon footprint by more than 90% and embedded energy by more than 50%. The ShAPE process has demonstrated the ability to process 100% of post-consumer scrap aluminum into extrusions that meet or exceed ASTM standards for building-grade alloys as well as for automotive applications (Hede 2024; Whalen et al. 2023b).

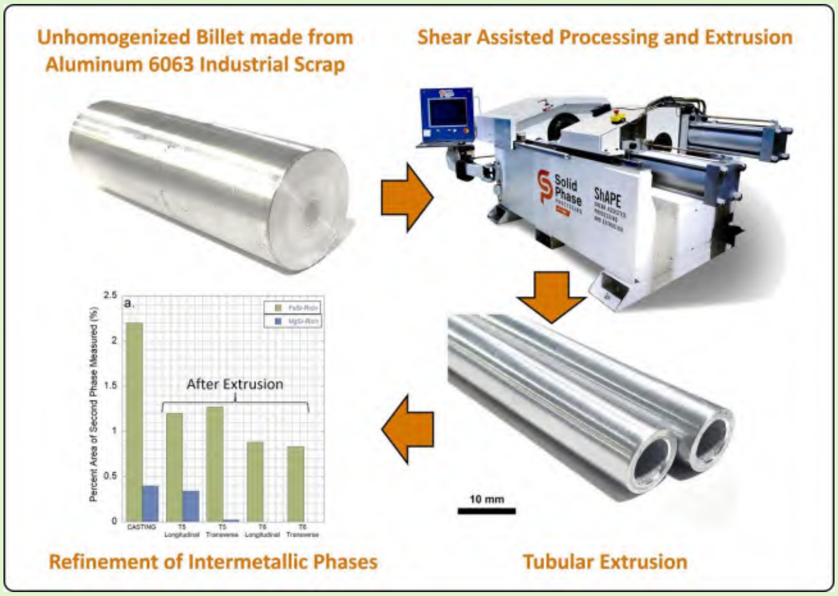

Figure 8. Illustration of using ShAPE to recycle aluminum, resulting in refined microstructure. Source: Whalen et al. 2023a.

Recyclable-by-Design Carbon Fiber Composites

When used in place of steel in vehicle components like hoods and roofs, carbon fiber composites can reduce the weight of a typical passenger car by 60%–70%—boosting fuel efficiency by up to 35%—without sacrificing strength. This swap can free up weight and space for bigger batteries in EVs, resulting in longer ranges and better energy efficiency. However, traditional carbon fiber composites are energy-, GHG emissions-, and cost-intensive, which may cancel out benefits from weight reduction during vehicle use. Such composites are also difficult to recycle.

The National Renewable Energy Laboratory (NREL) has successfully demonstrated and produced recyclable-by-design carbon fiber reinforced composites that leverage a bio-derived epoxy-anhydride/polyester covalently adaptable network (see Figure 10). These materials can be reshaped via thermoforming or recycled via a chemical depolymerization process. When both processes are used, the cost and GHG emissions of the material's second life drop by 90% to 95% compared to the first life of the material. Combining these processes is a promising solution for composites in vehicles; it could also benefit other applications such as wind turbine blades. NREL's work was supported by VTO's Composites Core Program in the Materials Technology subprogram in collaboration with the Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment (BOTTLE™) consortium funded by AMMTO and BETO.

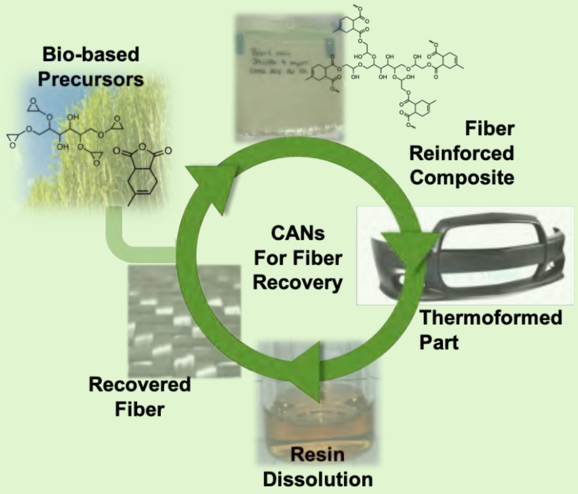

Figure 9. Illustration of recyclable-by-design carbon fiber reinforced composites utilizing bio-based covalently adaptable networks. *Source: Rorrer 2023*

3.2 Cross-Cutting R&D Opportunities, Challenges, and Enablers

Some R&D opportunities cut across Re-X pathways and can unlock multiple circular supply chains. These opportunities include reverse logistics, advanced sorting, quality assessment, and material flow analysis and tools.

3.2.1 Reverse Logistics

Reverse logistics encompasses the return of EOU or EOL products and materials back into supply chains for recirculation. Optimization of reverse logistics is critical to achieving increased product and material circularity because the challenges and costs associated with collection and transport are often key impediments. Illustrative examples are given in the following.

Opportunities include:

- Leveraging existing distribution networks for reverse logistics. The rise of e-commerce presents a new opportunity to expand collection utilizing distribution networks.
- Developing and adopting product-as-service models to align incentives, drive design for circularity implementation, and facilitate product collection.

Challenges include:

- Lack of insight into the distribution of products and materials.
- Difficulty collecting EOU or EOL products from consumers due to perceived inconvenience or lack of collection options.
- Consumer hesitancy to accept of product-as-service approaches due to loss of ownership control.

Enablers include:

- Partnerships along the supply chain for drop off programs at retailers or to utilize return trip transportation capacity.
- Drop off programs at retailers.
- Data sharing and inventory tracking.
- Emphasis on customer experience and value to support acceptance of product-as-service models.
- Incentivized return to a dealer network via customer credits to drive collection for remanufacturing.

3.2.2 Advanced Sorting

Many pathways that increase product and material circularity would benefit from more rapid and cost-effective sortation. This is the case at the product, component, and material level. Illustrative examples are given in the following.

Opportunities include:

- Increasing the rate and accuracy of product and component identification and disassembly, as well as lowering the cost of those activities.

- Reducing costs while boosting the efficiency and effectiveness of separating material streams for recycling to reduce contamination and improve recycled material quality.
- Improving insight into parts and materials in products via data tracking.

Challenges include:

- Inadequate labeling or a lack of access to necessary background data that hamper product and component identification.
- Robotic pick rate of materials in a materials recovery facility (MRF) that is slower than the rate of object identification.
- Automated pick up of large and oddly shaped objects.
- Separation of materials in mixed streams or from multimaterial products and components.
- Access to information relating to product history and material composition that limits assessments of product value, route to most optimal next use, and how to maximize value.

Enablers include:

- Combining computer vision, artificial intelligence, and large data sets with automated handling and disassembly technologies to increase speed and reduce costs associated with product identification and sortation.
- Faster and more flexible robotic systems for product separation.
- High speed, in-line diagnostics to increase purity.
- Product passports and databases.

Pilot Facility Advances Sorting and Separations

The ability to rapidly and economically separate products and materials is a cross-cutting challenge that is being addressed by leveraging advances in computer vision, robotics, artificial intelligence, and materials handling. The Biomass Feedstock National User Facility (BFNUF) at Idaho National Laboratory, funded by BETO, is the lead national research institution for material handling and mechanical processing. A $15 million upgrade was completed in 2023 to enhance biomass feedstock quality through expanded preprocessing capabilities, intelligent automation, and tools to advance fundamental knowledge of feedstock variability and material handling. The fundamental insights gained from biomass processing are being applied to the processing and recycling of materials, such as plastics and electronics (Idaho National Laboratory 2023a and 2023b).

3.2.3 Quality Assessment

Once products have been collected and sorted, they must still be assessed for quality before they can be routed for reuse, repair, or remanufacturing. Illustrative examples are given in the following.

Opportunities include:

- Routing of EV batteries to optimal next-life opportunity (back to vehicle, for energy storage, or to recycling) to maximize economic and environmental benefit.
- Reusing printed circuit boards or components such as microchips to overcome supply chain constraints and recover high value, high embodied energy products.

Challenges include:

- Lack of insight into remaining battery life and performance.
- Limited confidence of manufacturers to use recovered components due to concerns related to quality and availability.

Enablers include:

- Cost-effective, rapid, and accurate assessment of battery state of health.
- Automated assessment methods to rapidly test component functionality, coupled with datasets and models to support remaining lifetime.

3.2.4 Systems Analysis and Decision Support Tools

To create viable circular supply chains, insights are needed about the flow of products and materials and the potential impacts of technological, economic, and policy interventions. Systems-level analysis can inform high-level strategic planning and direct public and private investments toward impactful interventions. Tools to support decision making, such as LCA and techno-economic analysis (TEA), are necessary to ensure optimization of economic value while minimizing negative environmental and societal impacts. Increasing product and material circularity may not always be the optimal choice, and it is important to assess the potential unintended consequences. Illustrative examples are given in the following.

Opportunities include:

- Quantifying economic and environmental benefits of circularity to incentivize investment and business model changes. For example, using environmental product declarations (EPDs) when making procurement decisions.
- Routing of products and materials at EOU or EOL to minimize life cycle impacts and maximize economic benefits and security of supply.
- Prioritization of investments in opportunities where circularity can deliver largest impacts from the national perspective.

Challenges include:

- Lack of consensus around credible assessment of impacts and key terms, e.g., disagreement over the definition of recycling.
- Differences in LCA methodologies and limited up-to-date, transparent, and publicly available data.
- Missing product category rules (PCR) to enable EPDs for key products.
- Lack of insight into product and material stream disposition by location and evolution over time.
- Limited comprehensive data related to circularity impacts on decarbonization, community benefits, security of supply, and job creation.

Enablers include:

- Development of publicly accessible tools for LCAs and data. Standardization of LCA methodologies. Workforce development for LCA practitioners. Multicriteria decision analysis methods to compare across economic and sustainability metrics.
- Tools for determining optimal Re-X pathways with capability of considering multiple, interacting product and material streams.
- Accurate and spatially resolved material and product flows.

Whole Building Life Cycle Analysis Tools

Buildings are systems made up of many components such as mechanical, electrical, and plumbing subsystems. Analyzing the life cycle impact at the whole-building level can reveal opportunities for improvement that are not always clear at the component level. The Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) tool developed by Argonne National Laboratory has recently added a buildings module, funded by BTO. This tool was used to perform a whole-building life cycle assessment on a LEED-certified library in Chicago and demonstrated the impact of embodied carbon on the emissions payback period of a building. It also identified in this building type the embodied carbon hotspots on which to focus for maximum impact (Cai et al. 2022). Further research in this space is needed to expand our understanding of the trade-offs and synergies of operational and embodied emissions.

BTO aims to better quantify the emissions impact of the components themselves and to better understand how their roles within the building can be leveraged to reduce emissions at the whole building scale. For example, a heat pump designed for increased repair or recyclability can also contribute to increased lumber lifetime because it reduces humidity in the building. Modeling that captures the interplay of different components is needed to steer decisions that minimize the total impacts of a building across its full life cycle.

Material Flow Analysis

Sankey diagrams are useful for visualizing the net amount of material entering, recirculating, and leaving the economy. As an example, the material flow of steel in the United States in 2017 is shown in Figure 11. Sankey diagrams also provide important foundational data used to identify the size of a given opportunity by visualizing the magnitude of each material stream (e.g., for steel, automotive is a bigger opportunity than appliances). This visual data can help contextualize how much of the demand for a material can be met by recycled feedstock. In the case of steel, a significant fraction of the demand in the United States can be met by using scrap, but for other materials with increasing demand (e.g., aluminum), this is not true. Although Sankey diagrams are helpful visualizations, they do not capture the temporal nature of material flows (e.g., how long the material stays in use before reaching its EOL).

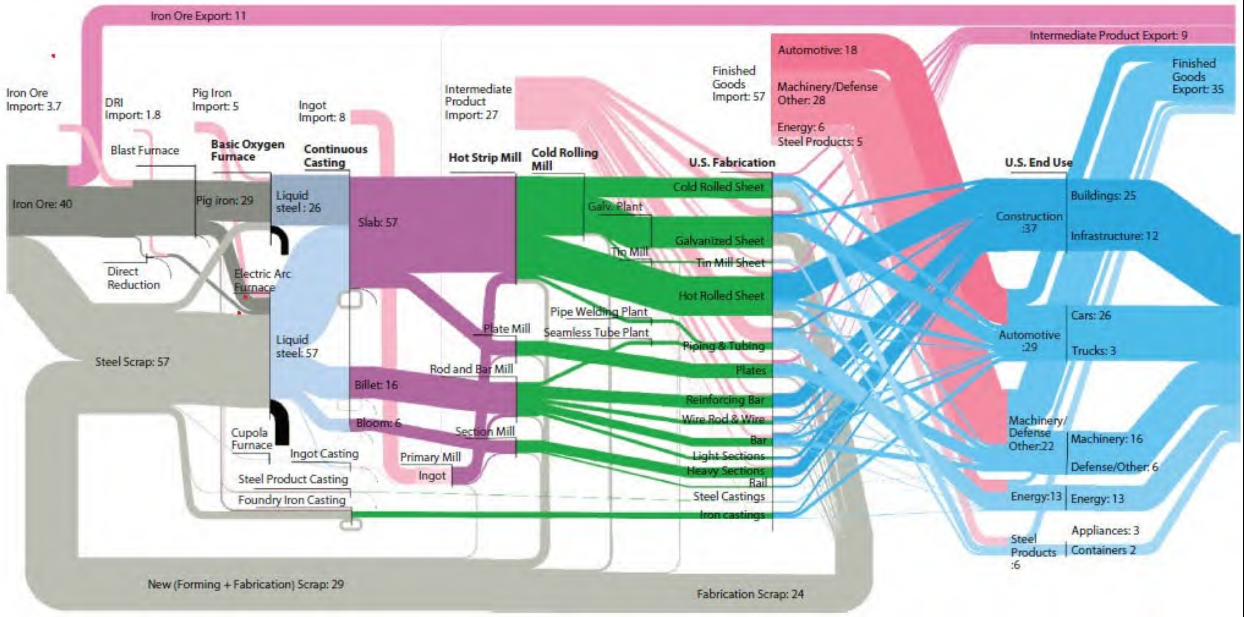

Figure 10. The U.S. steel cycle in 2017 with all values in million metric tons steel per year. *Source: Reck et al. 2024*

3.3 Nontechnical Challenges and Enablers

To realize the benefits of the technologies that will enable circularity, they will have to be adopted in the marketplace, often requiring a system-level shift, not just incremental improvements. These shifts cannot be done through technology development alone and will require the alignment of technology, policy, business models, and other factors to reach needed national-level impacts. This section discusses these factors and how they impact potential advancement of economywide circularity.

3.3.1 Incentives

Increasing circularity may be hampered by misalignment between those who bear the costs associated with design for circularity and those who reap the benefits. For example, modular design of a building for deconstruction and reuse may add costs and complexity during design and construction while the benefits of more optimal EOL may only be reaped decades in the future. When most of the costs and burdens of waste management fall upon municipalities, there is little incentive for producers to adopt practices to reduce those impacts because the costs are not reflected in the price of goods. Recycled materials may struggle to be cost competitive due to added collection and processing steps and because the environmental benefits, such as emissions advantages, may not be reflected in the price.

Multiple policy levers can help to align incentives. Sustainable procurement policies that leverage ecolabels are one option for creating increased demand for lower impact products. For example, the Federal Buy Clean Initiative was launched to incentivize the procurement of building materials with low embodied emissions, including those with recycled content. Measures in the Inflation Reduction Act of 2022 (IRA) provided funding to bolster the use of Environmental Product Declarations (EPDs) to measure the environmental impacts of building materials more accurately and transparently as a key enabler for the implementation of the Buy Clean Initiative. Other levers include costs of disposal as well as tax incentives for utilization of recycled materials. Extended producer responsibility (EPR) policies are one mechanism to attempt to align economic incentives to drive design changes by accounting for EOL management costs.

There may also be misalignment of incentives within a business. For example, the additional costs and time associated with redesign or material selection for remanufacturing or recycling may result in the product design department being viewed as less efficient. Alignment and support from the company leadership level are critical in these transformations. Corporate commitments related to sustainability goals are one mechanism to drive alignment within an organization.

3.3.2 Business Models and Supply Chain Development

Existing supply chains are complex. As illustrated in Figure 11, even just one steel component of an automobile can go through 6 processing steps, each one potentially happening at a different facility by a different company. In order for circularity to deliver substantial benefits, shifts in business models will need to establish and scale circular supply chains. The business model transformation necessary to drive circularity at scale will only be possible when the policy and regulatory landscape serves to align incentives across the supply chain and drive adoption. There must be an orchestration of business model evolution for circularity to scale successfully. This is why collaborative efforts—

such as precompetitive cooperation, public-private partnerships, and other efforts that bring together supply chain stakeholders to drive collective action—are critical.

One reason utilizing recycled materials is a focus is because if the recycled feedstock is similar to virgin material, little change is needed along the rest of the supply chain. However, other pathways such as remanufacturing or reuse may be able to deliver larger benefits than only material recovery via recycling. These other pathways require substantial changes in business models not only within a company but across the supply chain. Scaling remanufacturing and repair will not be possible without substantial redesign efforts coupled with business model innovations. For reuse to be effective, we need high collection rates, which will only be realized when the system scales.

3.3.3 Regulatory Harmonization and Standards

Realizing circular supply chains for products and materials can be hampered by a lack of harmonization in the regulatory landscape. Different policies related to EPR at the state level and internationally create uncertainty and increase cost of compliance for businesses who operate in multiple regions. Policy frameworks can support increased circularity by either reducing obstacles, such as with right-to-repair legislation, or by aligning incentives across the value chain, such as with EPR. Policies like deposit return schemes for beverage containers have been shown to substantially increase collection rates and improve purity of streams for recycling (Eunomia Research and Consulting 2023).

Harmonization of common definitions and metrics can benefit circular approaches. For example, differences in what is considered a recycling technology and what counts as recycled content in different regions create uncertainty and may hamper investment. Third-party verified ecolabels use specific criteria and definitions. Such labels help purchasers identify those products that meet specific environmental performance criteria (Environmental Protection Agency 2024).

Standards development and adoption are critical to scale of circular approaches and to boost confidence in claims related to sustainability (Morris et al. 2024). For example, standards support manufacturers in making design for circularity decisions, ensure interoperability to help scale reuse systems, and ensure consistency of classification of materials as waste and allocation of impacts of recycled materials in LCA.

3.3.4 Infrastructure

The amount and type of infrastructure to support circularity varies widely between regions. For example, the design and technology developed in MRFs across the country can vary substantially, with some having installed computer vision and robotics for enhanced separation and others relying entirely on manual sorting. Transportation infrastructure, such as rail lines, varies regionally and can affect the economic viability of recycling heavy commodity materials such as glass.

Substantially increasing reuse, remanufacturing, refurbishment, and recycling is not possible without additional infrastructure and facilities for collection, sortation, and processing. A massive scaling of infrastructure for collection, sorting, and processing will be needed to reach the National Recycling Goal to increase the U.S. recycling rate to 50% by 2030 and to increase other circular pathways. In September 2023, EPA announced the first round of selections from the Solid Waste Infrastructure Recycling Grant Program that was established as part of the Bipartisan Infrastructure Law. This is a major step toward building out the infrastructure needed.

3.3.5 Education, Outreach, and Behavior Change

Transitioning to more circular supply chains will not only require technology advancements but also behavior change. It can be difficult to assess costs and benefits of different pathways and product claims for consumers as well as industry and government decision makers. Consumers and businesses may be reluctant to accept recovered and recycled products and materials due to concerns related to reliability, safety, or quality.

Tools, education, and outreach can help to overcome these challenges. For example, analysis, technical assistance, and communication can help consumers and decision makers understand the tradeoffs between Re-X pathways and how to assess what the best options are. These approaches should be tailored to different audiences (consumers, policy makers, business leaders, and designers). Case studies, demonstrations, technical assistance, and education can address reluctance of consumers and businesses to adopt recovered and recycled products and materials due to reliability, safety, or quality concerns. Communities that are effectively engaged in understanding and influencing EOL and decommissioning plans for proposed technologies to be deployed in their area can help drive acceptance.

Leveraging social science approaches to drive behavior change is a large opportunity for product and material recovery. For example, providing consumers feedback via cart-tagging has been shown to reduce contamination in curbside recycling streams. However, the design of the messaging has a large impact on its effectiveness (The Recycling Partnership 2023).

4 Activities Advancing Product and Material Circularity

EERE supports a wide range of work to advance product and material circularity in support of its mission. Most of these activities are focused on applied R&D, covering technology readiness levels ranging from ~2 to 6, and fostering partnerships to advance toward demonstration and deployment. In this section of the strategy document, areas of focus for different offices will be summarized, followed by more detailed discussion of specific technologies or materials.

4.1 Office Focus Areas

The focus areas for different EERE offices are summarized in the following.

AMMTO focuses on:

- Composites recycling and redesign for improved repair and recycling.
- Improved critical materials recycling technology for and recovery from e-scrap.
- Battery recycling and remanufacturing.
- Plastics recycling technology development and design for recyclability.
- Analysis and data related to material flows, supply chain analyses, and Federal LCA Commons.
- Smart manufacturing technologies that enable more efficient and economic manufacturing processes, including those needed for circularity such as enhanced sorting, defect and performance assessments, and design for circularity.
- Design, manufacturing technologies, and material development for circularity.
- Leveraging advanced manufacturing and materials for repair and remanufacturing.

BETO focuses on:

- Plastics recycling technology development and design for recyclability/biodegradability.
- Material recovery from MSW.
- Advanced sorting and separations of feedstock streams for recycling.

BTO focuses on:

- Minimizing product and building life cycle emissions.
- Creating whole-building life cycle assessment methodologies.
- Recycling or reuse of construction and demolition waste.
- Adaptive reuse of existing buildings.
- Building with deconstruction in mind.

GTO focuses on:

- Developing sustainable construction materials for enhanced geothermal systems.
- Lithium recycling and recirculation of geothermal fluids.
- Repurposing existing energy infrastructure for geothermal energy.

HFTO focuses on:

- EOL for fuel cell and electrolyzer systems.
- PGM (platinum and iridium) reclamation and membrane recycling.
- Development and use of analysis tools.
- Designing for recyclability and efficient and automated disassembly.
- Reuse of recovered materials and components.

IEDO focuses on:

- Sustainable feedstocks (such as clean hydrogen, bio-based feedstocks, and EOL materials, like scrap steel and recycled plastics) for emissions-intensive industries (such as steel, cement, chemicals, and glass).
- Better Plants waste reduction network.

SETO focuses on:

- Developing low-cost and scalable reuse, refurbishing, repair, and recycling of PV materials.
- Increasing module efficiency, durability, and energy generation lifespan.
- Building partnerships and working groups with stakeholders across the entire life cycle to increase solar circularity.
- Redesigning PV cells and modules for less precious metal incorporation and more facile recycling.
- Collecting and analyzing EOL, decommissioning, recycling, and toxicity testing data to establish a baseline on current practices and to inform future directions.

VTO focuses on:

- Recycling of metals and composites (e.g., carbon fiber and resins).
- EV battery recycling, reuse in second-life applications, and circularity.

WETO focuses on:

- Composites and magnet circularity and recycling.
- Modeling and analysis for design for circularity.

- Turbine maintenance and repair.
- Refurbishment/reuse/resale of wind energy technologies.

WPTO focuses on:

- Reuse of carbon fiber composites in lower performance applications.
- Recovery and recycling of thermoplastics.
- Exploring life extension of energy conversion devices by repair using additive manufacturing.

SA focuses on:

- Building foundational systems-level circularity analysis capabilities.

4.2 Product and Material Focus Areas

Multiple offices have activities related to product and material circularity that are complementary in addressing specific technology or material spaces. The range of EERE focus areas and key institutes or facilities are summarized in Table 5.

Table 5. Summary of Material, Product, and Cross-Cutting Activities

	Area	Offices	Focus and Key Institutes or Consortium	
Materials	Critical Materials[a]	AMMTO; multiple	Electronics, magnets, motors, batteries; recycling REEs; PGMs	CMI Hub
	Steel and Aluminum	IEDO; VTO; AMMTO	Alloy design; recycling processes	REMADE
	Construction Materials	IEDO; BTO; GTO	Cement and concrete, glass, asphalt; utilizing recycled feedstocks	
	Plastics	AMMTO; BETO; IEDO	Redesign; recycling	BOTTLE; CUWP; REMADE, RAPID
	Composites	AMMTO; WETO; VTO	Fiber/resin recovery; recycling, redesign, reuse	IACMI
Products	Buildings and Infrastructure	BTO; GTO	Adaptive reuse and retrofitting; recycling	ABC Center; Wells of Opportunity
	Batteries	VTO; AMMTO	EV battery to storage; recycling	ReCell
	Wind	WETO	Wind blades, magnets; recycling, repurposing, repair	
	Solar	SETO	PV modules and components; recycling, redesign	Solar PARC
	Electrolyzers and Fuel Cells	HFTO	Recycling, redesign	H_2CIRC
Cross-Cutting	Analysis, models, and data	SA; multiple	Analysis tools and data to support LCA; modeling to identify opportunities	
	REMADE	AMMTO	Metals, fibers, plastics, electronics; remanufacturing, reuse, recycling, redesign	

	BFNUF	BETO	MSW, biomass, plastics; reparations and preprocessing
	MDF	AMMTO; VTO; WETO	Metals, composites; remanufacturing, repair, recycling

[a] Critical materials are treated separately from battery materials in this report.

The following sections will discuss the material, product, and cross-cutting focus areas as well as analysis, modeling, and data. Each section will highlight the importance of the focus area to EERE, the current challenges, and the technology advancements needed. Key references, activities, and EERE investments will be summarized in a table. Note that there are connections between the materials and technologies (e.g., high relevance of critical materials for batteries and composites for wind).

4.2.1 Critical Materials

Note that aluminum, while considered a critical material for the clean energy technology, is discussed in Section 4.2.2.

4.2.1.1 Importance

DOE has identified the “electric 18,” elements and materials that have been deemed to have moderate to severe supply chain risk in the near and mid-term and that are important for clean energy technologies. These include rare earth materials (neodymium, praseodymium, dysprosium, and terbium) used in magnets in EV traction motors and wind turbine generators; materials needed for batteries for EVs and stationary storage (cobalt, lithium, nickel, fluorine, and natural graphite); platinum group metals used in hydrogen electrolyzers and fuel cells (platinum and iridium); semiconductors for efficient lighting and power electronics (gallium and silicon carbide); lightweight alloys (magnesium and aluminum); solar (silicon); and major materials with importance in electrification (copper and electrical steel) for transformers and electric machines (U.S. Department of Energy 2023a). Expanding domestic supply of critical materials can be realized in the near term via recovery from existing e-scrap and in the longer term via recovery from newly deployed clean energy technologies like EVs, solar panels, and offshore wind. As critical materials demand continues to grow, new approaches will be required to ensure sufficient supply.

4.2.1.2 Challenges

The composition of e-scrap is not well documented, can fluctuate depending on time and location, and can have a low concentration of critical materials. The economics of critical materials recovery can be prohibitive. Supply chains for recovery of critical materials products for reuse, remanufacturing, and repurposing are not mature. Quality assessment methodologies for critical containing products such as batteries, motors, and solar panels are lacking, which hampers development of second-life applications.

Technology advancements needed include:

- Cost-effective collection and device disassembly of electronics and motors for component recovery, remanufacturing, and recycling.
- Identification of approaches to unlock second-life uses for motors and generators from EVs and offshore wind energy.
- Selective, flexible, modular, and adaptive recycling processes leveraging the co-recovery of valuable noncritical materials.
- Critical materials recycling processes that reduce chemical waste generation and lower costs.
- Approaches that identify feedstocks for recycling that contain high concentrations of critical materials and characterization methods to assess composition and concentration of critical materials in feedstocks.

4.2.1.3 Activities and Key Investments Related to Critical Materials

Strategies, workshops, and reports include:

- One of the four pillars of DOE’s critical minerals and materials program strategy is to build the circular economy, including remanufacture, refurbish, repair, reuse, recycle, and repurpose for all materials used in a modern economy to extend the lifetime of materials and/or partially offset the need for virgin material extraction.
- The 2023 DOE Critical Materials Assessment evaluates the criticality of materials based on their importance to the energy sector and their supply risk (U.S. Department of Energy 2023a).
- In 2022, researchers supported by the CMI Hub published a review of recycling rare earths (Fujita, McCall, and Ginosar 2022).
- Released in 2021, DOE’s *Strategy to Support Domestic Critical Mineral and Material Supply Chains* provided a foundation to balance efforts across three pillars: diversify supply chains, develop substitutes, and improve reuse and recycling (U.S. Department of Energy 2021c).

Analysis, models, and data include:

- The Global Critical Materials tool models the business decisions of key supply chain stakeholders to identify possible disruptions in critical material supply chains and evaluate mitigation strategies (Riddle et al. 2020). EOL recovery and recycling pathways can be incorporated.

- The Critical Materials Life Cycle Assessment Tool is a web-based software tool that can be used to conduct life cycle analysis on the production of critical materials and products containing critical materials. The current version focuses on REEs. The tool was developed by Purdue University through support by the CMI Hub.

Institutes, centers, and consortia include:

- The CMI Hub research focus area “Building a Circular Economy” (which was formerly known as Driving Reuse & Recycling during CMI Phase II) will conduct research around the themes of Green Chemistry Approaches, Process Intensification and Preprocessing to Improve Manufacturing Efficiency, and Manufacturing Methods to Enable Insertion of Recycled Products into Supply Chains. CMI Hub has funded multiple projects related to critical materials recycling. A summary of their work related to recycling is included in their Year 10 Cumulative Report (Critical Materials Institute 2023). Notable achievements include MSX and ADR processes (discussed in Section 3.1.5) as well as EC-Leach for electrochemical recovery of critical materials from battery black mass and the E-RECOV process for recovery of palladium and copper from e-scrap. The CMI Hub continues to explore bio-based separations.
- REMADE Institute has projects focused on system analysis, remanufacturing, and recycling of electronics.

Funding includes:

- AMMTO Fiscal Year 2024 (FY24) Electronics Scrap Recycling Advancement Prize will award up to $4 million to substantially increase the production and use of critical materials recovered from e-scrap.
- AMMTO Fiscal Year 2023 (FY23) DE-FOA-0003155 Topic 3 – Critical Material Recovery from Scrap and Post-Consumer Products will award between $1.2 million and $4 million for projects to develop and validate approaches to recycle or recover critical materials from post-consumer products—including, but not limited to, design for recycling and reuse and de-risking critical material recovery from waste and manufacturing scrap.
- AMMTO awarded $8.8 million in funding for three projects focused on recycling of silicon, copper, PGMs, and REEs under the Fiscal Year 2022 (FY22) DE-FOA-0002864 Topic Area 2.1: Materials Circularity Regional Demonstrations.
- Fiscal Year 2020 (FY20) Small Business Innovation Research (SBIR) FOA-2146 Phase I Release 2 Topic 6c on Critical Materials Supply Chain, Area of Interest ii

on Energy Efficiency Manufacturing of Critical Materials, included processes to recycle or recover critical materials from EOL. Three Phase I projects were awarded for REE recycling from e-scrap, two of which went on to Phase II.

4.2.2 Steel and Aluminum

4.2.2.1 Importance

Increasing the circularity of high-volume commodity metals like aluminum and steel plays an important role in economy-wide decarbonization and supporting the clean energy transition. Scaling clean energy technologies demands large amounts of these metals. However, primary production results in high emissions.

Steel

Steel is critical for infrastructure, buildings, transportation, and the buildout of clean energy technologies. Iron and steel manufacturing is one of the most energy-intensive industries worldwide. While the U.S. steel sector is among the best globally in terms of GHG emissions per metric ton of product—due to the high fraction of remelted scrap in U.S. steel production compared to that of other nations—the United States is the world's largest importer of steel (Hasanbeigi and Springer 2019). Although steel has a relatively high recycling rate, increased reuse of steel products and components offers opportunities for reduced emissions and decreased imports of steel to the United States.

Aluminum

The use of aluminum in vehicles is increasing due to the need for lightweighting and the adoption of EVs. As of 2021, 65% of aluminum production in the United States was secondary production. Building out the recycling supply chain with increased diversion of scrap from landfill and increased domestic processing of Zorba (mixed nonferrous metal scrap typically obtained from shredding and sorting of EOL products) was identified as a pathway contributing to aluminum decarbonization (U.S. Department of Energy 2023b).

4.2.2.2 Challenges

There are limited established supply chains that recirculate products or parts rather than scraping them for recycling. Accumulation of unwanted impurities in both steel and aluminum scrap results in down-cycling or the need to dilute with virgin material. For example, excessive copper and tin cause hot shortness during hot rolling, ruining the surface quality of the steel for the most demanding applications. Similarly, aluminum scrap suffers from the gradual accumulation of unwanted impurities such as iron, manganese, and other alloying elements. These impurities result in devaluation where scrap is used to produce lower-value cast products.

Technology advancements needed include:

- Design tools and data flows to increase reuse of structural elements in construction.
- Additive and hybrid manufacturing processes to reduce costs and increase performance of repaired or remanufactured products.
- Convergence in alloy design and selection to facilitate recycling stream quality.
- Design and processing of alloys for greater contamination resistance.
- Advanced sorting that allows separation not only by metal class but by alloy type.
- New technologies and approaches to avoid or reverse the accumulation of tramp elements, including processes that refine or eliminate tramp elements from the melt or microstructural engineering that reduces the impact of contamination on performance.

4.2.2.3 Activities and Key Investments Related to Steel and Aluminum

Strategies, workshops, and reports include:

- The 2022 DOE Industrial Decarbonization Roadmap identifies that circular economy approaches can support decarbonization of energy-intensive industries such as iron and steel.

Institutes, centers, and consortia include:

- REMADE Institute has several projects related to improving metal recycling processes, alloy design, and vehicle design for improved recycling. Additionally, the Institute supports work focused on software to assist in design for remanufacturing as well as advanced technology for metal component remanufacture and repair. They have also published a material flow analysis for carbon steel and stainless steel (Reck 2023) and have ongoing efforts related to aluminum.
- The Manufacturing Demonstration Facility has demonstrated that its advanced manufacturing processes, software, and metrology expertise can be leveraged for repair and remanufacturing of metal products, for example, cast iron engine blocks (Sridharan 2021).
- The CMI Hub project 3.2.11 uses cerium to inactivate residual impurities to improve recyclability of aluminum.

Analysis, modeling, and data include:

- In 2021, VTO funded an expansion of the GREET model to investigate differences in recycling rates and recycled content for major automotive materials. The expanded model also included EOL recycling methodology for steel, wrought aluminum, and cast aluminum to allow users to see how EOL “credit” from material recycling can impact life cycle burdens.

Funding includes:

- IEDO’s FY24 Energy and Emissions Intensive Industries FOA (DE-FOA-0003219) will award up to $4.7 million for improving steel recyclability by reducing tramp metal contaminants.
- VTO’s Lightweight Metals Core Program has provided over $15 million aimed at developing a suite of low-cost, advanced manufacturing processes that can improve the local properties of castings, allow higher performance and lighter weight, and potentially enable lower cost and fewer alloys to simplify the supply chain and recycling path.
- AMMTO provided $2 million in funding for a project focused on aluminum recycling from the FY22 Multitopic FOA DE-FOA-0002864 Topic Area 2.1: Materials Circularity Regional Demonstrations.
- The Advanced Manufacturing Office’s FY20 Multitopic FOA (DE-FOA-0002252) awarded $3.4 million in funding for projects focused on increasing recycling and reuse within the iron and steel industry.
- In 2019, VTO provided $1 million in funding for ShAPE of Lightweight Automotive Components (CRADA 418) to produce automotive components from secondary aluminum.

4.2.3 Construction Materials (Cement and Concrete, Glass, and Asphalt)

4.2.3.1 Importance

Construction materials such as cement, concrete, asphalt pavements, and glass are energy and emissions intensive with high production volumes that are expected to grow further as the United States replaces aging infrastructure and transitions to renewable energy such as solar and wind.

Cement and Concrete

Cement acts as the binder in concrete, significantly influencing its structural performance, and contributes nearly 90% of concrete’s GHG emissions. The cement industry is considered a “hard-to-abate” sector and is responsible for 2% of U.S. GHG emissions and 1% of U.S. energy consumption (U.S. Department of Energy 2022a).

Glass

Using cullet (crushed glass) from recycling streams lowers energy requirements, reduces virgin raw material inputs, and reduces CO_2 emissions from decomposition. Increasing the amount of recycled glass cullet used during glass manufacturing from 30% to 90% can reduce GHG emissions from container glass production by more than 60% (Avery and Carpenter 2023). The volume of glass produced in the United States, along with the associated GHG emissions, has the potential to grow substantially in coming years due to the expansion of buildings and infrastructure as well as to increased demand from solar PV manufacturing.

Asphalt

Asphalt pavements are widely used in roadways and other paving applications. Cradle-to-gate emissions associated with asphalt mix accounts for approximately 0.3% of total GHG emissions in the United States (Shacat, Willis, and Ciavola 2022). There is potential to increase recycling of asphalt pavement and to use recycled plastics in asphalt pavements (National Academies of Sciences, Engineering, and Medicine 2023).

Challenges

Cement and Concrete

Recycled concrete is most commonly used as road base or as recycled concrete aggregate. These applications displace the need for natural aggregate but do not reduce demand for new concrete in construction. There is a fraction of unreacted cement in concrete which may be possible to recover for reuse. However, recycling the hydrated cement from set concrete for use as binder in new cement requires reversal of the hydration reaction. Additionally, the cost of transporting concrete for second-life applications or recycling can be prohibitive. Direct reuse of concrete structures is inhibited by lack of design for deconstruction and by the conservative nature of the construction sector.

Glass

Contamination, large travel distances, and a lack of infrastructure can cause cullet to be less desirable due to the risk of a high rejection rate. Recycling of specialty glass, such as for solar panels, requires that it is not mixed with other glass waste streams. Utilizing post-consumer glass can be more expensive than landfilling. Reuse of intact glass can be difficult due to risk of breakage during transport and the need for pieces to be of desired dimensions. In the case of solar, changes in module size and specification may limit direct glass reuse.

Asphalt

Achieving sufficient durability of asphalt formulations with high recycled content is difficult.

Technology advancements needed include:

- For cement and concrete:
    - Development of supplementary cementitious materials from recovered material streams such as demolition waste or post-consumer glass.

  - Technologies to recover and recycle unreacted cement from concrete demolition waste to reduce the amount of new cement needed in a concrete mixture.
  - Technologies and monitoring approaches that extend the lifetime of concrete structures via repair.
  - Modular construction approaches to enable reuse of concrete elements.
- For glass:
  - Glass formulations and/or processing routes that are more tolerant of contaminants and/or enable innovative use of post-consumer recycled glass.
- For asphalt:
  - Formulations of asphalt leveraging recycled plastic waste streams and delivering higher durability.

4.2.3.2 Activities and Key Investments Related to Construction Materials

Strategies, workshops, and reports include:

- In 2024, IEDO hosted a glass decarbonization workshop which included a focus on glass circularity.
- A 2023 NREL study identified increased usage of recycled glass cullet in glass manufacturing as a substantial decarbonization benefit (Avery and Carpenter 2023).

Institutes, centers, and consortia include:

- REMADE has several projects focused on using recycled plastics and tires for asphalt.

Funding includes:

- IEDO’s FY24 Energy and Emissions Intensive Industries FOA (DE-FOA-0003219) Topic Area 4: Decarbonizing Building and Infrastructure Materials – Cement and Concrete, Asphalt, and Glass includes utilization of recycled materials.
- GTO and the Office of Science are partnering with the Center for Coupled Chemo-Mechanics of Cementitious Composites at one of the Energy Earthshots™ research centers in Brookhaven National Laboratory to develop sustainable construction materials for enhanced geothermal systems.

4.2.4 Plastics

4.2.4.1 Importance

Due to their combination of light weight, durability, and ease of processing, plastics can provide benefits that reduce impacts during use, from their role in insulation and sealing of buildings to their role in light weighting vehicles. Both in the United States and globally, plastics, including synthetic fibers, are one of the fastest-growing waste streams, yet have one of the lowest recycling rates. Virgin plastic production is energy and emissions intensive and there is increasing concern about the impacts of plastic pollution on human health and the environment (Landrigan et al. 2023). Increasing circularity has the potential to reduce demand for virgin plastics, lowering related energy use and embodied emissions, and to decrease both macroscopic and microscopic plastic pollution.

4.2.4.2 Challenges

Due to the variety of compositions (both polymers and additives) as well as product formats (rigid containers, flexible and multilayer films, fibers and textiles), the collection and effective recycling of plastics is particularly challenging. Polymers of different composition are thermodynamically immiscible, making separation of waste streams critical for mechanical recycling. Emerging advanced recycling technologies, such as pyrolysis, solvolysis, or depolymerization also require sorted waste streams. Halogen containing polymers or additives, such as polyvinyl chloride or flame retardants, are particularly problematic.

Technology advancements needed include:

- Development of new polymers that deliver performance requirements while having more optimal EOL, such as enhanced recyclability or composability.
- New recycling technologies that can handle a wider range of inputs (e.g., mixed waste streams and additives).
- Improved sorting technologies that can separate mixed olefins as well as halogen containing materials.
- LCA and TEA studies comparing multiple pathways for EOL polymers including mechanical recycling, advanced recycling approaches, and conversion to chemical feedstocks or fuels.

4.2.5 Activities and Key Investments Related to Plastics

Strategies, workshops, and reports include:

- The Strategy for Plastics Innovation was released in 2023 to make domestic processing of plastic waste more economically viable and energy-efficient, to develop new and improved plastic materials lacking the EOL concerns of incumbent materials, and ultimately to reduce plastic waste accumulation (U.S. Department of Energy 2023d).

- Joint workshops hosted by BETO and AMMTO in 2019 (Plastics for a Circular Economy Workshop) and 2023 (Transitioning to a Sustainable, Circular Economy for Plastics Workshop) brought together a diverse range of stakeholders to provide input on current challenges and opportunities to address and reduce plastic waste (U.S. Department of Energy BETO 2020 and U.S. Department of Energy 2024b).

Analysis, modeling and data include:

- Lawrence Berkeley National Laboratory led a study that quantified U.S. plastic flows from production to disposal and developed scenarios to increase plastic circularity (Hendrickson et al. 2024).
- A CE sustainability analysis framework study combined LCA and material flow analysis (MFA) to simultaneously evaluate the life cycle impacts and circularity metrics of implementing different CE strategies in production of plastic packaging. PET bottles were used as an example (Gracida-Alvarez et al. 2023).
- The Plastic Parallel Pathways Platform combines LCA and agent-based modeling within a dynamic MFA structure to compute the environmental impacts of different recycling options under various behavioral interventions (Walzberg, Ghosh, and Uekert 2023).
- An ongoing AMMTO-funded lab project seeks to understand the amount and location of infrastructure needed to meet plastic recycling targets and the economic and environmental impacts of such an expansion.

Institutes, centers, and consortia include:

- The REMADE Institute has funded several projects related to plastic and textile recycling, including flexible film recovery at materials recovery facilities as well as tire remanufacturing and recycling.
- The Rapid Advancement in Process Intensification Deployment Institute is focused on efficiency and decarbonization of the chemicals and fuels sector and its scope includes use of waste feedstocks such as plastics. It was launched in 2017 and renewed in 2023.
- BOTTLE™ Consortium is funded by AMMTO and BETO at $30 million for three years and has been renewed. It focuses on developing new chemical upcycling strategies for today’s plastics and redesigning tomorrow’s plastics to be recyclable-by-design. It has a strong focus on analysis.
- The Center for the Upcycling of Waste Plastic (CUWP) is a multi-university initiative aimed at providing technical, environmental, and economic information on chemical recycling of plastic wastes. It is supported by $10 million from the FY20 BETO multi-topic FOA (DE-FOA-0002203).

Energy Earthshots include:

- The Clean Fuels & Products Shot™ focuses on decarbonizing the fuel and chemical industry through alternative sources of carbon to advance cost-effective technologies with a minimum of 85% lower GHG emissions by 2035. Mobilization of biomass and waste feedstocks as well as understanding sustainability implications are focus areas.

Funding includes:

- AMMTO and BETO's FY21 Single-Use Plastics Recycling FOA (DE-FOA-0002473) awarded $14.5 million for research and development to cut waste and reduce the energy used to recycle single-use plastics like plastic bags, wraps, and films.
- The FY21 BETO Scale-up and Conversion FOA (DE-FOA-0002396) funded a $2.25 million project related to plastic recycling.
- AMMTO and BETO's FY20 BOTTLE FOA (DE-FOA-0002245) awarded $13.4 million to projects that support the development of advanced plastics recycling technologies and new plastics that are recyclable-by-design.
- The FY20 BETO multi-topic FOA (DE-FOA-0002203) awarded $4 million for projects related to polymer recycling and recyclable polymer design.
- The FY23 IEDO multi-topic FOA (DE-FOA-0002997) awarded $9.3 million for a project related to advanced recycling of tires.

4.2.6 Composites

4.2.6.1 Importance

Polymer composites are light-weight materials with high strength and toughness. They combine reinforcing fibers in a matrix and are used in a wide range of manufactured goods that contribute to decarbonization. For example, they reduce transportation emissions by reducing weight and are used in wind turbine blades and in tanks for storing hydrogen. Due to the energy intensity required to produce carbon and glass fibers as well as the polymeric matrix material, composites have high embodied emissions.

4.2.6.2 Challenges

Traditional thermoset matrices generate large amounts of manufacturing scrap and render repair and recycling problematic due to an inability to reshape the material. Changes in fiber length and surface chemistry during recycling negatively affect mechanical performance when the recovered fibers are reused in composites. Identification of applications for and qualification of recycled materials from composites is challenging because of a lack of insight into the source of recycled feedstocks and resulting properties.

Technology advancements needed include:

- Development of reformable composite matrices—such as thermoplastic resins or vitrimers—to reduce production waste, allow for repair or reshaping, and enable mechanical recycling.
- Development of advanced recycling technologies that allow recovery of both matrix and fibers.
- Manufacturing methods to enable recovered fibers to be aligned and deliver performance closer to that of traditional continuous fiber composites.

Note: Composites circularity work related specifically to wind turbines is discussed in section 4.2.8.

4.2.6.3 Activities and Key Investments Related to Composites

Institutes and consortia include:

- The Institute for Advanced Composites Manufacturing Innovation (IACMI) has funded multiple projects focused on composites inspection and recycling.
- The MDF has a focus on composite recycling from advanced manufacturing processes.

Funding includes:

- The BOTTLE FOA (DE-FOA-0002245) includes some work relevant to composites recycling.
- AMMTO, BTO, and OE FY22 Multi-topic FOA DE-FOA-0002864 Topic Area 1.2: Harsh Environment Materials funded one project for $2 million aiming to produce ceramic matrix composites from recycled carbon fibers.
- FY24 VTO DE-FOA-0003120 Topic Area 2: Recycling of electric drive vehicle battery accessory components provides approximately $2 million for recycling of plastic and polymer composite electric drive vehicle battery accessory components through research, development, and demonstration.
- The FY19 BETO multi-topic FOA (DE-FOA-0002029) awarded $3.6 million for projects related to recyclable thermosets and composites recycling.
- VTO's FY22 Program Wide FOA DE-FOA-0002611 awarded $2.5 million to develop low-cost, high-performance, sustainable, and multi-functional composites from recycled materials for automotive applications.
- VTO's FY23 SBIR/STTR (Small Business Technology Transfer) Phase I (DE-FOA-0002903) Subtopic C56-10c: Recycling of Polymer Composites for Vehicle Decarbonization awarded $400K for two projects: Upcycling Of Polymer

Composites For Vehicle Decarbonization and Producing Multifunctional Automotive Composites with Sustainable Plant Based Graphene.

- VTO's FY23 Lab Call (DE-LC-0000021) in Thrust 3 Area: Circularity and sustainability of polymer composites awarded $4.2 million to produce and commercialize industrial-grade polymers and automotive composites from circular or renewable feedstocks with properties rivaling petroleum-derived materials while reducing manufacturing costs by $5/kg.
- VTO's FY23 Program Wide FOA (DE-FOA-0002893) Topic Area 7: Circularity and Sustainability of Polymer Composites for Vehicle Lightweighting and Decarbonization awarded $8 million for four projects on composites recycling and circular economy to reduce the embodied energy of vehicle components and decrease polymer composites' carbon footprint.

4.2.7 Buildings and Infrastructure

4.2.7.1 Importance

As building operations become more efficient, tackling life cycle GHG emissions associated with building material manufacturing, transport, installation, maintenance, and end-of use disposal will be crucial for achieving the nation's objective to decarbonize the U.S. building stock by 2050 (U.S. Department of Energy 2024a). The embodied emissions in buildings can be minimized by repurposing buildings via adaptive reuse, reducing the quantity of new materials required, utilizing salvaged or recycled materials, and designing for deconstruction and reuse. These approaches should also complement actions to use less material in the building or retrofitting processes, for example, by leveraging prefabricated construction approaches. Preventing release of refrigerants during decommissioning of heating and cooling systems or building demolition can contribute to decarbonization. There is an opportunity to repurpose existing energy infrastructure to enable geothermal heating and cooling of buildings.

4.2.7.2 Challenges

There is a lack of quality data on embodied emissions at the national, whole-building, and product scales, as well as a lack of consensus on standardization of whole building LCA methods. Adaptive reuse of buildings is challenging due to the lack of standardization of the existing building stock and due to code and zoning barriers. Most embodied emissions are associated with decisions made during building design and construction, so engagement at both the design and material selection phases is critical.

Technology advancements needed include:

- Recovery and recycling of construction and demolition debris into new building materials, including technologies like insulation and flat glass.

- Modular construction techniques incorporating design for reuse and data tracking to enable second life opportunities.
- Technologies and approaches to effectively recover refrigerants at EOL for cooling systems and/or building demolition/deconstruction.

4.2.7.3 Activities and Key Investments Related to Buildings and Infrastructure

Strategies, workshops, and reports include:

- In 2024, DOE released a U.S. Buildings Blueprint that includes action the federal government can take to meet specific targets for increasing building energy efficiency, accelerating onsite emissions reductions, transforming the grid edge, and minimizing embodied life cycle emissions (U.S. Department of Energy 2024a).
- BTO is developing an assessment of the challenges and opportunities for embodied carbon reduction in buildings.
- BTO's Advanced Building Construction Initiative integrates energy efficiency solutions into highly productive U.S. construction practices for new buildings and retrofits.
- Lawrence Berkeley National Laboratory released the Assessing Opportunities for Circularity in Buildings report in 2022 (Gursel et al. 2022).

Institutes, center, and consortia include:

- The Advanced Building Construction Collaborative aims to facilitate a coalition of industry leaders to develop, demonstrate, and scale high-performance, energy-efficient construction, for both retrofit and new build, to transform the built environment and reinvigorate the construction industry.
- GTO's Wells of Opportunity initiative aims to use existing oil and gas wells for geothermal energy production. Oil and gas wells can be used to harness geothermal energy in two ways: the retrofitting of inactive or unproductive wells or co-production with active wells.

Analysis, modeling, and data include:

- The BTO funded Life-Cycle Analysis of Advanced Building Construction Technologies will develop methodologies and generate data to conduct LCA of advanced building construction technologies for building components and whole buildings.
- The Material Flow through Buildings framework allows for consistent impact comparison for alternative major building materials, construction practices, and use/recycling strategies for materials and buildings (Gursel et al. 2022).

- In 2022, Argonne National Laboratory updated the R&D GREET Building LCA Module. The module is designed to conduct and compare detailed and transparent LCA of building materials/components/technologies, as well as whole buildings and building designs.

Technical Assistance includes:

- BTO hosted a webinar series in 2020 exploring frameworks and techniques researchers use to evaluate the energy use of buildings over their entire lifespans, from construction to operation to eventual destruction.
- In 2024 BTO released a reference guide on Embodied Carbon Reduction in New Construction (U.S. Department of Energy 2024c).
- The DOE Better Buildings, Better Plants Waste Reduction Network brings industry-leading organizations together to demonstrate successful waste management solutions.

Funding includes:

- BTO's FY21 Advanced Building Construction FOA DE-FOA-0002099 awarded $26.3 million for new technologies capable of enhancing building energy performance without disrupting occupant comfort. These technologies should be deployed quickly, affordably, and with minimal onsite construction for both existing building stock and new construction projects.
- BTO's FY21 Envelope Retrofit Opportunities for Building Optimization Technologies prize will award up to $5 million for the development of advanced robotics capabilities and controls for building envelope retrofits.
- GTO's FY22 Community Geothermal Heating and Cooling Design and Deployment FOA (DE-FOA-002632) will provide up to $13 million to help communities design and deploy geothermal district heating and cooling systems that contribute to decarbonizing the buildings sector. This can include retrofitting of existing energy systems.
- GTO's Wells of Opportunity FOAs in 2020 (DE-FOA-0002227) and 2021 (DE-FOA-0002525) provided $22.4 million in funding for projects that advance geothermal energy by retrofitting inactive or unproductive wells or enabling co-production at active wells.
- GTO's 2023 Bipartisan Infrastructure Law Enhanced Geothermal Systems Pilot Demonstrations FOA (DE-FOA-0002826) provides funding to support the Enhanced Geothermal Shot™ through advanced drilling approaches and materials. This FOA has four topics with relevance to product and material circularity. For example, Topic 1 focuses on enhanced geothermal systems demonstrations

utilizing existing infrastructure proximal to existing geothermal/hydrothermal development with immediate potential for electrical power production.

4.2.8 Batteries

4.2.8.1 Importance

Batteries play a critical enabling role in transportation decarbonization and energy storage to facilitate the broader adoption of intermittent renewables such as wind and solar. The demand for EVs and stationary storage alone is projected to increase the size of the lithium battery market five- to 10-fold by the end of the decade (IEA 2024). Battery recycling and repurposing will help meet this rise in demand, bolster the domestic supply chain for battery critical materials, and reduce the environmental impacts of mining new critical materials.

4.2.8.2 Challenges

Due to potential fire hazards, safely transporting batteries can account for up to 40% of overall recycling costs (California Environmental Protection Agency 2022). Publicly available, reliable information on state, volume, or costs to recondition retired batteries is limited. Battery designs make assessing and repairing/replacing individual cells difficult. Variability in lithium-ion battery design results in costly manual disassembly processes. Each battery requires development of specialized recycling processes. Recycling of emerging battery technologies such as lithium iron phosphate are not economical due to lack of high value materials recovered. Incorporation of recycled materials into the battery supply chain is difficult because of lack of insight into volumes and properties of outputs.

Technology advancements needed include:

- Development of battery recycling processes with improved efficiency in terms of economics and costs.
- Product designs for batteries that are easier to disassemble, processes that automate disassembly, and more effective separation of housing materials from active battery materials.
- Technologies to rejuvenate batteries, increasing performance and extending useful life.
- Rapid state of health diagnostics to assess remaining useful life and optimize next life routing.
- Innovative approaches to reduce the costs of transporting batteries, including combining storage with transportation to enable full truck load shipping.
- Technologies for safely de-energizing, neutralizing, shredding, deactivating, or otherwise preprocessing the battery to allow transportation with less restrictive designations.
- Digital battery passports.

4.2.8.3 Activities and Key Investments Related to Batteries

Strategies, workshops, and reports include:

- The Battery Critical Materials Supply Chain Challenges and Opportunities report summarizes the results from a 2020 EERE Request for Information (RFI) and the R&D Battery Critical Materials Supply Chain Virtual Workshop. Recommendations include implementing a national lithium battery recycling policy to recover and reuse key materials (U.S. Department of Energy 2021b).
- In 2021, VTO supported the development of the National Blueprint for Lithium Batteries to help guide investments to develop a domestic lithium battery manufacturing value chain (Federal Consortium for Advanced Batteries 2021).
- In 2023, an EERE supported report from NREL on Electric Vehicle Lithium-ion Battery Life Cycle Management provided a technical overview, described opportunities and obstacles to reuse and recycle EV batteries, and surveyed worldwide initiatives to promote and regulate the responsible management of batteries throughout their life cycle (Pesaran, Roman, and Kincaide 2023).
- A white paper resulted from the 2023 lithium-ion battery recycling workshop hosted by Li-Bridge with representatives from the across the supply chain as well as from government and national labs. (Li-Bridge 2024).

Analysis, modeling, and data includes:

- EverBatt is an Excel-based battery recycling process and supply chain model from Argonne National Laboratory supported by VTO.
- The Lithium-Ion Battery Resource Assessment Model provides critical insight into lithium-ion battery manufacturing, reuse, and recycling across the global supply chain under dynamic conditions.
- The Battery Lifetime Analysis and Simulation Tool Suite assesses battery lifespan and performance for behind-the-meter, vehicle, and stationary applications.
- In 2023, Argonne National Laboratory released an R&D GREET Battery module in beta.
- DOE’s Battery Policies and Incentives database can be used to search for policies and incentives related to batteries developed for EVs and stationary energy storage. Users can find information related to EV or energy storage financing for battery development, including grants, tax credits, and research funding; battery policies and regulations; and battery safety standards.

Institutes, center, and consortia include:

- The CMI HUB funded multiple projects related to battery recycling and reuse during Phase II of operations (2018-2023) (projects 3.1.11 – 3.1.15, 3.3.11).
- VTO funded the ReCell Center is national collaboration of industry, academia and national laboratories working together to advance recycling technologies along the entire battery life cycle for current and future battery chemistries. The center focuses on directly recycling materials from spent batteries to minimize energy use and waste by eliminating mining and processing steps.
- REMADE Institute has funded projects related to battery reuse (21-01-RM-5019, 23-01-RM-6007), remanufacturing (21-01-RM-5039), and disassembly (21-01-RM-5083).

Funding includes:

- In 2019, DOE launched the Lithium-Ion Battery Recycling Prize with $5.5 million in prizes. DOE extended the prize in 2023 with an additional $7.4 million to identify innovative solutions for collecting, sorting, storing, and transporting spent and discarded lithium-ion batteries.
- The Bipartisan Infrastructure Law (BIL) FY23 Electric Drive Vehicle Battery Recycling and Second Life Applications FOA (DE-FOA-0003120) Topic Area 1 provides approximately $35 million to reduce the costs associated with transportation, dismantling, and preprocessing of EOL EV batteries for recycling.
- VTO's FY22 BIL Electric Drive Vehicle Battery Recycling and Second Life Applications FOA (DE-FOA-0002680) provided $60 million for second-life applications for EV batteries, as well as for new processes to recycle materials back into the battery supply chain.
- AMMTO's FY23 Recycling-Remanufacturing Lab Call (DE-LC-0000027) provided $2 million to develop room temperature processes for recycling and reuse of electrodes and for recycling of electrolytes for lithium-ion batteries.

Others include:

- Office of Manufacturing and Energy Supply Chains' (MESC) FY23 Battery Manufacturing and Recycling Grants Program (DE-FOA-0003099) is a $3 billion program designed to provide grants to ensure that the United States has a viable domestic manufacturing and recycling capability to support a North American battery supply chain.
- In 2023, VTO, on behalf of MESC, issued the Bipartisan Infrastructure Law Consumer Electronics Battery Recycling, Reprocessing, and Battery Collection FOA (DE-FOA-0002897) with $125 million to support the recycling of consumer electronics batteries and battery-containing devices.

- In 2024, ARPA-E announced the Catalyzing Innovative Research for Circular Use of Long-lived Advanced Rechargeables program (DE-FOA-0003303) that will fund up to $30 million for projects aiming to develop technologies to support a circular domestic supply chain for EV batteries through regeneration, repair, reuse, and remanufacture.

4.2.9 Wind

4.2.9.1 Importance

Cumulative U.S. wind power generating capacity grew to more than 144 gigawatts by the end of 2022 and there is potential for five to ten times that amount to be installed by 2035 to meet domestic decarbonization goals (U.S. Department of Energy Wind Energy Technology Office 2023b and Denholm et al. 2022). While the majority of materials used in wind turbines are easily recyclable, composite materials make up 6%–14% of a wind turbine mass and have limited EOL options in the United States outside of landfilling (U.S. Department of Energy Wind Energy Technology Office 2023a). Of particular focus for circularity are those materials without commercial-scale recycling options, such as composites and critical materials like REEs in permanent magnet synchronous generators. Interventions that extend wind turbine longevity, such as advanced monitoring and repair, also contribute to increased clean energy production. The Wind Energy Technologies Recycling Research, Development, and Demonstration Program was authorized by the Energy Act of 2020 and appropriated funds through the Infrastructure Investment and Jobs Act, otherwise known as the BIL.

4.2.9.2 Challenges

Costs associated with decommissioning and transport of composite structures or materials from wind turbines can be high, and the process can be as complicated logistically if located in remote or difficult to access locations. Because landfills tend to be the closest EOL option, they are also often the cheapest EOL option for decommissioned blades.

Technology advancements needed include:

- Approaches that enable on-site size reduction of blades into shapes needed for repurposing for structural applications and that address logistics challenges.
- Advanced monitoring and in-field repair for turbines to extend lifetimes and increase reliability.
- Remanufacturing approaches for components.
- Viable routes for reuse of entire turbines decommissioned due to repowering for second life in distributed power generation.

Note: Challenges related specifically to composites material development and circularity are addressed in Section 4.2.5.

4.2.9.3 Activities and Key Investments Related to Wind

Strategies, workshops, and reports include:

- The Institute for Advanced Composites Manufacturing Innovation hosted a workshop in 2021 exploring the possibility of developing a circular economy for wind blades.
- A 2021 study assessed Wind Turbine Blade Material in the United States: Quantities, Costs, and End-of-Life Options (Cooperman, Eberle, and Lantz 2021).

Institutes, center, and consortia include:

- WETO supports developing advanced blade inspection techniques and improving repair capabilities as part of the Blade Reliability Initiative and the Drivetrain Reliability Collaborative.

Analysis, modeling, and data includes:

- Working with multiple national laboratories, WETO is assessing the current state of material recycling and recovery technologies for wind energy components. This effort will provide data to DOE that will inform high-priority research and development needs in the U.S. wind industry, including information to support community engagement and outreach.
- NREL led an analysis to understand how stakeholder behavior affects wind blade EOL (Walzberg et al. 2022).
- A 2022 case study used NREL's Circular Economy Lifecycle Assessment and Visualization Framework (CELAVI) to investigate the influence of pathway costs and level of wind turbine installations on supply chain circularity and environmental impacts (Ghosh et al. 2022).

Technical assistance includes:

- The Wind Energy End-of-Service Guide is an informational resource for communities to better understand repowering and decommissioning processes for wind turbines and related infrastructure as well as recycling or disposal of blades.

Funding includes:

- WETO's FY23 Incubator program awarded $150K to two projects related to wind turbine blade repair.
- In 2023, WETO announced over $4 million in funding for projects related to wind turbine blade recycling, life extension, repair, and monitoring through SBIR and STTR awards.

- WETO’s Wind Turbine Materials Recycling Prize will award $5.1 million in prizes to develop cost-effective domestic recycling options for fiber-reinforced composites and REEs present in wind turbines.

4.2.10 Solar

4.2.10.1 Importance

Solar energy technologies are essential to reaching decarbonization targets. To achieve grid decarbonization by 2035 and net-zero economy-wide emissions by 2050, the DOE Solar Futures Study estimates that solar energy would need to expand from currently providing 5% of U.S. electricity to 45% by 2050 (U.S. Department of Energy 2021a). Enhancing the durability and repairability of solar panels can prolong their lifespan, thus keeping solar panels generating electricity longer and reducing the number of solar panels needing disposal. An increase of two to three years in average module lifetime could decrease waste by two to three million metric tons by 2050 (Solar Energy Technologies Office 2024).

4.2.10.2 Challenges

Costs of repairing, reusing, or recycling panels compared to new installs. Evaluating the safety and performance of panels removed from initial deployments before reinstallation. Decomissioning and transportation for EOL components is costly, and it is still significantly cheaper to landfill ($1-5 per module) than to recycle ($15-45 per module) (U.S. Department of Energy SETO 2022). The laminate structure of modules makes material separation and extraction through recycling challenging to scale economically, particularly to recover high purity silver, which accounts for ~60% of the recoverable value of the module. Reducing contamination and creating streams of solar grade glass for recycling back into solar applications are also difficult tasks.

Technology advancements needed include:

- Design and material selection that enable disassembly of solar panels to facilitate recycling or repair.
- Scalable hardware and software solutions for robust maintenance.
- Assessment tools and standards to determine if removed solar panels have sufficient quality and lifetime left to be reused safely or to optimize recycling.
- Analysis to understand optimal markets for second use panels or recovered materials.
- Technologies aimed at increasing transportation packing efficiency of decommissioned components.
- High-throughput and low-cost processing for recycling and material recovery from nonoperational modules.

4.2.10.3 Activities and Key Investments Related to Solar

Strategies, workshops, and reports include:

- In 2020, SETO funded an NREL study to assess the global status of practice and knowledge for EOL management for crystalline silicon PV modules (Heath et al. 2020).
- Solar Photovoltaic Module Recycling: A Survey of U.S. Policies and Initiatives: Researchers at NREL surveyed existing and proposed policies related to PV recycling in the United States to provide insight on policy and industry standards that can help enable PV module recycling (Curtis et al. 2021a).
- NREL's 2021 report A Circular Economy for Solar Photovoltaic System Materials: Drivers, Barriers, Enablers, and U.S. Policy Considerations analyzed the logistical, economic, and regulatory factors that could both impede and encourage EOL options for PV systems in the United States. (Curtis et al. 2021b).
- In 2022, SETO released the Photovoltaics End-of-Life Action Plan, which outlines research activities that can enable safe and environmentally sound handling of PV EOL materials. It was informed by a 2021 workshop and RFI related to solar EOL (U.S. Department of Energy Solar Energy Technology Office 2021a and U.S. Department of Energy Solar Energy Technology Office 2021b).
- The 2022 Solar Photovoltaics Supply Chain Deep Dive Assessment identified that recycling should become standard practice to facilitate domestic material availability (U.S. Department of Energy 2022c).
- Best Practices at the End of the Photovoltaic System Performance Period considers the costs and other factors for each EOL option for a PV system (Curtis et al. 2021c).

Institutes, center, and consortia include:

- REMADE Institute has projects focused on recycling (21-01-RR-5014) and design for circularity (18-01-DE-07, 21-01-DE-5028) of PV.
- The CMI Hub has funded work (Project 3.1.3) related to cadmium telluride PV recycling.

Analysis, modeling, and data includes:

- The Renewable Energy Materials Properties Database (REMPD) quantifies how much and what type of materials are needed to construct wind energy and solar power devices and plants.

- NREL's Photovoltaics in the Circular Economy tool tracks solar module materials from virgin extraction and refinement through EOL, incorporating some circular pathways.

Funding includes:

- The FY23 SETO MORE PV FOA (DE-FOA-0002985) will provide $20 million over three years for research and development projects to create innovative and practical approaches to increase the reuse and recycling of solar energy technologies. This will include an $8 million partnership focused on technologies and methods to enable low-cost reuse, refurbishing, repair, and recycling of PV materials. The partnership will also identify best practices for safe disposal of these materials, including data collection, analysis, and working groups to enable effective collaborations and technology transfer.
- SETO's FY23 Small Innovative Projects in Solar funded one project for $250,000 to quantify the effects of repowering PV systems to gain a better understanding of the resulting system energy yield, cost, sustainability impacts, remaining useful lifetime, and energy equity.
- SETO's FY22 Photovoltaics Research and Development FOA (DE-FOA-0002582) funded $6.05 million to develop design and materials separation techniques for PV recycling, which will result in a more resilient supply chain and lower the environmental impacts of PV modules entering the waste stream.
- In the FY22–24 Lab Call, SETO funded one project for $800,000 to study issues around handling PV panels at the end of their useful life and to lead an international working group on PV Sustainability Activities (International Energy Agency PVPS Task 12).
- The FY22 Small Innovative Projects in Solar (SIPS) (DE-FOA-0002606) funded three projects for $825,000 related to recycling or repair of concentrating solar-thermal power and PV.
- SETO funded projects that consider recycling and EOL for perovskite PV in FY20 for $350K and in FY21 for $200,000.
- SETO awarded $2.7 million from the FY19 DE-FOA-0002064 for two projects aimed at enabling reuse of III-V semiconductor substrates in manufacturing.
- AMMTO funded a project in the FY22 DE-FOA-0002864 focused on recycling silicon from solar cells into battery materials.

4.2.11 Electrolyzers and Fuel Cells

4.2.11.1 Importance

The rapid growth in hydrogen technology markets also highlights the need to improve how hydrogen systems are handled at EOL. To secure supply of PGMs and other critical materials, recovery and recycling of components from EOL systems is crucial. For instance, manufacturing the proton exchange membrane electrolyzers and fuel cells required to reach the gigawatt scale will require orders of magnitude more iridium than today's global supply, which is sourced primarily from South Africa and Russia (U.S. Department of Energy 2022b). It is estimated that recycling could reduce the GHG emissions associated with PEM electrolyzers and fuel cell deployment in the United States by 16%t by 2050 (Uekert, Wikoff, and Badgett 2023).

4.2.11.2 Challenges

Recycling approaches that utilize incineration to recover PGMs from membrane electrode assemblies can release hydrofluoric acid. The variety of membrane chemistries makes recycling difficult due to challenges of segregating spent membrane materials by ionomer type. It is also difficult to separate catalysts containing PGMs from membranes without destroying the ionomer.

Technology advancements needed include:

- Technologies to recover platinum and iridium catalysts from fuel cells and electrolyzers.
- Approaches that can recover ionomer membranes, bipolar plates, gas diffusion layers, and porous transport layers from PEM for reuse or recycling.
- Automated disassembly processes and design for recyclability processes.
- Interventions to extend component lifetimes or second-life applications for older electrolyzers.

4.2.11.3 Activities and Key Investments Related to Electrolyzers and Fuel Cells

Strategies, workshops, and reports include:

- In May 2022, HFTO, in collaboration with NREL and Oak Ridge National Laboratory, hosted a Manufacturing Automation and Recycling for Clean Hydrogen Technologies Experts Meeting[3] focused on identifying opportunities for domestic manufacturing of PEM and solid oxide fuel cells and accompanying systems

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[3] https://www.energy.gov/eere/fuelcells/manufacturing-automation-and-recycling-clean-hydrogen-technologies-experts-meeting

through process automation, as well as for their EOL remanufacturing and recycling. A report is forthcoming.

- The 2023 study Electrolyzer and Fuel Cell Recycling for a Circular Hydrogen Economy assessed economic and environmental impacts of electrolyzer and fuel cell recycling (Uekert, Wikoff, and Badgett 2023).

Institutes, center, and consortia include:

- HFTO's 2023 DE-FOA-0002922 Topic 6 provided $50 million in funding to establish the Circular Recycling for the Hydrogen Economy (H2CIRC) consortium to develop and demonstrate recycling technology approaches to address EOL and critical supply chain challenges for PEM fuel cells and electrolyzers. The goal is to provide a blueprint for the hydrogen industry to efficiently and sustainably recover and recycle materials and components.

Funding includes:

- HFTO's 2023 Topic 5 of the Bipartisan Infrastructure Law: Clean Hydrogen Electrolysis, Manufacturing, and Recycling FOA DE-FOA-0002922 provided $10 million in funding for two projects to design and manufacture non-PFSA membranes for fuel cell applications that may improve recycling.
- HFTO, IEDO, and AMMTO provided $800K in funding for FY23 Small Business Innovation Research-Small Business Technology Transfer Phase 1 awards (DE-FOA-0002903) related to fuel cell and electrolyzer recycling. HFTO funded additional projects related to thermal management of fuel cells for increased durability ($600K), bipolar plate durability and refurbishment ($1 million), non-PFSA membranes for electrolyzers and fuel cells ($600,000), and alkaline exchange membranes for electrolyzers ($1.2 million).
- HFTO's FY23 Lab Call - Advanced Materials, Components, and Interfaces for Electrolyzers designated $3.2 million to projects for improved electrolyzer use and performance that included innovative non-PFSA and alkaline exchange membrane designs, PGM-free catalysts, and additional advanced component design.
- HFTO's FY24 Lab Call Topic 2 - Innovative Concepts in non-PFSA High Temperature Proton Exchange Membrane Fuel Cells for Heavy-Duty Transportation Applications designated $6 million for projects that may improve recyclability by eliminating fluorinated membranes.

4.2.12 Cross-Cutting Areas

This section focuses on sorting, separations, and remanufacturing technology needs that cut across material and technology focus areas. Institutes and facilities, such as REMADE, BFNUF, and MDF that can be leveraged across multiple focus areas are included. Cross-cutting analysis, models, and data needs are discussed in the next section.

4.2.12.1 Importance

Mixed waste streams, such as MSW and automotive shredder residue, contain substantial volumes of recyclable materials. These recyclable materials could be recovered through more efficient and cost-effective separation methods. Improved identification, sorting, and separation processes would benefit all multiple product and material streams. Challenges with separation of materials in MSW and scrap streams are similar to separation challenges for biomass. Thus, technology advances for biomass can be leveraged for other material streams.

4.2.12.2 Challenges

The ability to produce recycled materials that are of similar quality and cost competitive with virgin alternatives is hampered by the cost of sorting systems and limited rates of identification. Robotic systems struggle to rapidly manipulate products and to pick oddly shaped items. Material stream contamination is often not able to be reduced without hazardous waste generation, high energy use, or high costs.

Technology advancements needed include:

- Materials and approaches for design for disassembly, including modular designs, high strength debondable adhesives, and reversible joining techniques.
- Autonomous robotic disassembly.
- Robotic or other approaches to more rapidly grab or divert target materials identified in mixed material streams, such as in MRFs or recycling streams.
- Cost-effective automated sorting leveraging advanced sensors to identify different materials and separation technologies to create recyclable material streams.

4.2.12.3 Activities and Key Investments Related to Cross-Cutting Areas

Strategies, workshops, and reports include:

- U. S. Drive aims to release a roadmap by 2025 for lightweight, sustainable, and critical automotive materials. The scope for sustainable materials includes recycled plastics/polymers, metals, and reinforced composites.
- In 2022, DOE released the Industrial Decarbonization Roadmap, which identifies material efficiency as a crosscutting approach needed to reach net zero (U.S. Department of Energy 2022a).
- The 2023 DOE Pathways to Commercial Liftoff: Industrial Decarbonization report includes discussion of how recycling can contribute to emissions reduction for a variety of materials (U.S. Department of Energy 2023b).

- Design for Recycling Principles Applicable to Selected Clean Energy Technologies: Crystalline-Silicon Photovoltaic Modules, Electric Vehicle Batteries, and Wind Turbine Blades is an EERE-funded study on the application of design for recycling principles to clean energy technologies (Norgren, Carpenter, and Heath 2020).
- A 2017 remanufacturing roadmap captures extensive industry engagement to identify research and development priorities to advance the state of U.S. remanufacturing (Rochester Institute of Technology 2017).

Institutes, center, and consortia include:

- The REMADE Institute is a public-private partnership established in 2017 with an initial $70 million in funding from AMMTO. It is the only national institute focused entirely on developing innovative technologies to accelerate the transition to a circular economy in the United States. REMADE focuses its efforts on driving down the cost of technologies essential to reuse, remanufacture, and recycle energy-intensive materials: metals, including aluminum and steel; fibers, including paper and textiles; polymers, including plastics; and e-scrap.
- The Biomass Feedstock National User Facility is the lead national research facility for material handling and mechanical processing. A $15 million upgrade funded by BETO and completed in 2023 expanded the BFNUF's preprocessing capabilities, intelligent automation, and tools to advance fundamental knowledge of feedstock variability and material handling.
- The MDF supported by AMMTO has extensive capabilities related to additive manufacturing that can be leveraged for remanufacturing and repair. MDF also focuses on composites recycling.

Funding include:

- BETO's FY21 Feedstock Technologies and Algae FOA (DE-FOA-0002423) Topic Area 1: Characterization of Municipal Solid Waste to Enable Production of Conversion-Ready Feedstocks funded several projects focused on advanced separations and sorting.
- AMMTO launched the Re-X Before Recycling Prize in 2023 with $5.6 million in prizes to incentivize innovation to unlock new or expanded supply chains that can reintegrate EOU products into the economy via re-use, repair, refurbishment, remanufacturing, and/or repurposing.

4.2.13 Analysis, Models, and Data

This section focuses on cross-cutting and overarching analysis, models, and data. Those specific to products and materials discussed above are incorporated in the relevant section.

4.2.13.1 Importance

Robust strategic analysis at a variety of levels—from targeted technology comparisons to broad economy-wide supply chain modeling—is needed for EERE and other federal agencies to make impactful investments in circular strategies. Analysis to evaluate and compare circular pathways, understand system interactions, quantify circularity benefits, and anticipate barriers to technology can support decision making and prioritization of investment. Such analysis requires accurate, timely, and spatially resolved data and models that can assess circular products and material flows. Analysis can address questions such as: How do circular strategies alter the ability to deploy clean energy technologies? What are potential trade-offs between different circular strategies or between circular strategies and other alternatives?

4.2.13.2 Challenges

Access to accurate granular information around product and material flows is limited, particularly for post-industrial flows. Difficulties in analysis and modeling include incorporating cross-sectoral interactions, broadening life cycle boundaries, adding dynamic change to static models, probing social and behavioral barriers to adoption, and quantifying and communicating uncertainty in analysis outcomes.

Technology advancements needed included:

- Updating of background data sets from models such as GREET in the Federal LCA Commons.
- Approaches that can assess the impacts of increased circularity across the whole economy and that can incorporate cross-sectoral interactions.
- Incorporation of policy impacts on circularity as well as insights into societal impacts into modeling.

4.2.14 Activities and Key Investments Related to Analysis, Models, and Data

Strategy, workshops, and reports include:

- A 2022 NREL report mapped the opportunity to model the circular economy using tools funded by EERE (Upasani et al. 2022).
- The Sustainable Manufacturing and the Circular Economy report details five analysis case studies (food waste, plastics recycling, EV battery recycling, nickel-metal hydride battery recycling, and cement manufacturing electrification) to understand material consumption, waste generation, trade-offs, and adoption of circular strategies (U.S. Department of Energy Advanced Manufacturing Office 2023).
- In 2021, an EERE-funded study explored whether a new sustainability assessment method is needed for the circular economy (Walzberg et al. 2021).

Institutes, center, and consortia include:

- REMADE has undertaken an analysis to provide a baseline for measuring progress in reusing metal, fibers (textiles and paper), polymers, and e-waste utilizing 2017 U.S. material flows.

Analysis, modeling, and data includes:

- Circular Economy Lifecycle Assessment and Visualization Framework (CELAVI) is a dynamic and flexible tool that models the impacts of clean energy supply chains during the transition from a linear to a circular economy.
- Agent-Based Models assess how interactions between a system's actors influence circulation. EERE has funded case studies related to recycling wind turbines, photovoltaics, hard disk drives (Walzberg et al. 2023a), and plastics (Walzberg et al. 2023b).
- Materials Flow through Industry tool identifies and assesses energy and material demands and carbon emissions from the supply chain. It can be used to investigate circular strategies, including ongoing work on the iron and steel sector, glass recycling, and wind turbine EOL plans.
- GREET is an LCA model developed at Argonne National Laboratory that assesses a range of life cycle energy, emissions, and environmental challenges that can be used to guide decision-making, research and development, and regulations related to transportation and the energy sector. The model is currently undergoing an expansion of modeling efforts of energy and emissions credits of EOL of vehicle components. GREET tools are also available that focus on batteries and buildings.
- The Techno-economic Energy & Carbon Heuristic Tool for Early-Stage Technologies aids users in estimating potential energy, carbon, and cost impacts of a new technology in a streamlined spreadsheet tool that integrates LCA and TEA methods.
- REMPD quantifies how much and what types of materials are needed to construct wind energy and solar power devices and plants, summarizing the significant uses, availability, countries of origin, and some physical (such as thermal, electrical, and mechanical) properties for these materials.
- The Federal LCA Commons is an interagency community of practice for LCA research methods. It is a central point of access to a collection of data repositories for use in LCA.

5 Future Work Related to Product and Material Circularity

As demonstrated in this strategy, increasing product and material circularity delivers economic and environmental benefits and plays a vital role in advancing the overall mission of EERE. Previous EERE investments are having an impact across the mission space not only by advancing technologies toward deployment but also by influencing investment and decision-making. Circular supply chains are complex and require integration of a diverse group of stakeholders to succeed. Continued, coordinated efforts and investments are needed across EERE to overcome the substantial challenges identified and discussed in this strategy document and to achieve EERE's ambitions in circularity.

EERE will leverage the three-step framework described in Section 2.2 to prioritize work that is impactful and has a high likelihood of advancing the establishment of circular product and material supply chains. Prioritization of investment in opportunities where circularity has the largest impact on advancing decarbonization, community benefits, U.S. security of supply, and job creation at the national level will require data collection and analysis, including understanding geographical hot spots.

Informed by the prioritization framework to identify opportunities to maximize impact of circularity, future EERE efforts will likely include advancing the following technologies, data and analysis, and collaborations:

- More rapid and cost-effective product, component, and material identification, sorting, and separation.
- Design for circularity, including design and material approaches to enable Re-X and leveraging digital tools and approaches for system monitoring, assessment, and tracking.
- Data, analysis, and modeling tools to support whole life cycle analysis and support decision-making, including during product design and business model development.
- Technical assistance to support the transition to more circular product and material flows in the economy.
- Clean energy technology deployment via increasing recovery and reuse of critical materials.
- Collaboration amongst stakeholders to facilitate the design of circular products, supply chains, and ecosystems by leveraging EERE's convening power.

Although technology development is needed to achieve increased product and material circularity, policy and business model development will play an essential role in the deployment of these technologies. By improving awareness of these and other factors that influence deployment, EERE can better align the RD&D strategy towards technologies with a high likelihood of driving national-level impact.

Product and material circularity is also critical to advancing DOE's mission. EERE will contribute by engaging with departments across the agency. As technology is advanced through EERE efforts, close coordination and alignment with the Office of Infrastructure are crucial for successful technology deployment. EERE must incorporate fundamental insights and discoveries from the Office of Science as well as ARPA-E into its projects and approach addressing circularity. Examples of engagement with offices across DOE include:

- Coordination with the Basic Energy Sciences program and the Biological and Environmental Research program on fundamental scientific insights and discoveries that can overcome critical bottlenecks related to material separation, recycling, and design for circularity.
- Collaboration with the Office of Clean Energy Demonstrations to demonstrate critical advances such as those for breakthrough recycling technologies.
- Engagement with MESC to strengthen and scale America's clean energy supply chains, particularly for critical materials.

While EERE and DOE play a critical role in research, development, demonstration, and deployment of technologies to advance product and material circularity, a whole-of-government approach is essential to unlock the potential of increased circularity and achieve our decarbonization goals. EERE will continue to actively engage in interagency collaborations that serve to advance circularity. Examples of areas of interagency engagement include:

- Coordination with the National Institute of Standards and Technology on data and decision tools, materials science, environmental impact assessment, and standards to advance the circular economy.
- Collaboration with the White House Office of Science and Technology Policy, the EPA, the General Services Administration, the Department of Agriculture, and others that support initiatives to encourage the establishment of circular supply chains such as the Federal Buy Clean Initiative, the development of EPDs, the Federal LCA Commons, and national strategies on plastics and recycling.
- Engagement with NSF to leverage fundamental insights and workforce development related to LCA and to collaborate on their applied work.

As is evident by the importance of coordination, collaboration, and stakeholder engagement, EERE sees this as critical to enabling impact. EERE will continue to engage with a diverse range of stakeholders to inform their programming in this space through a variety of mechanisms including RFIs, workshops, roundtables, and interagency working groups. This stakeholder strategy includes engaging with existing industrial and interagency entities to ensure EERE employs best practices and approaches that maximize the desired impacts of EERE programs and activities. In addition, DOE and EERE priorities will be advanced through a variety of funding opportunities including FOAs, lab calls, prizes, and other mechanisms.