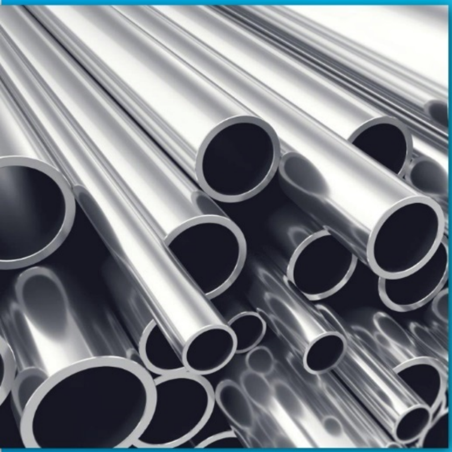

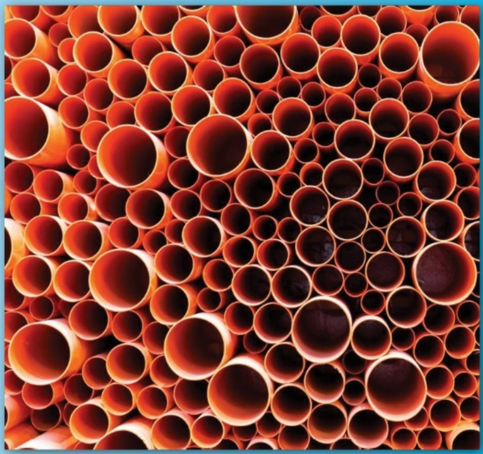
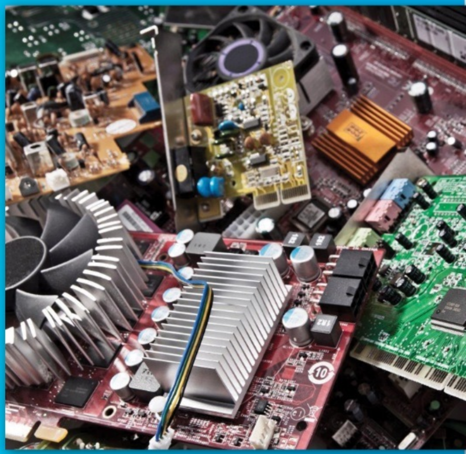

REMADE Technology Roadmap

2018

REMADE INSTITUTE

NEXIGHT GROUP

JANUARY 2018 Preliminary Public Draft

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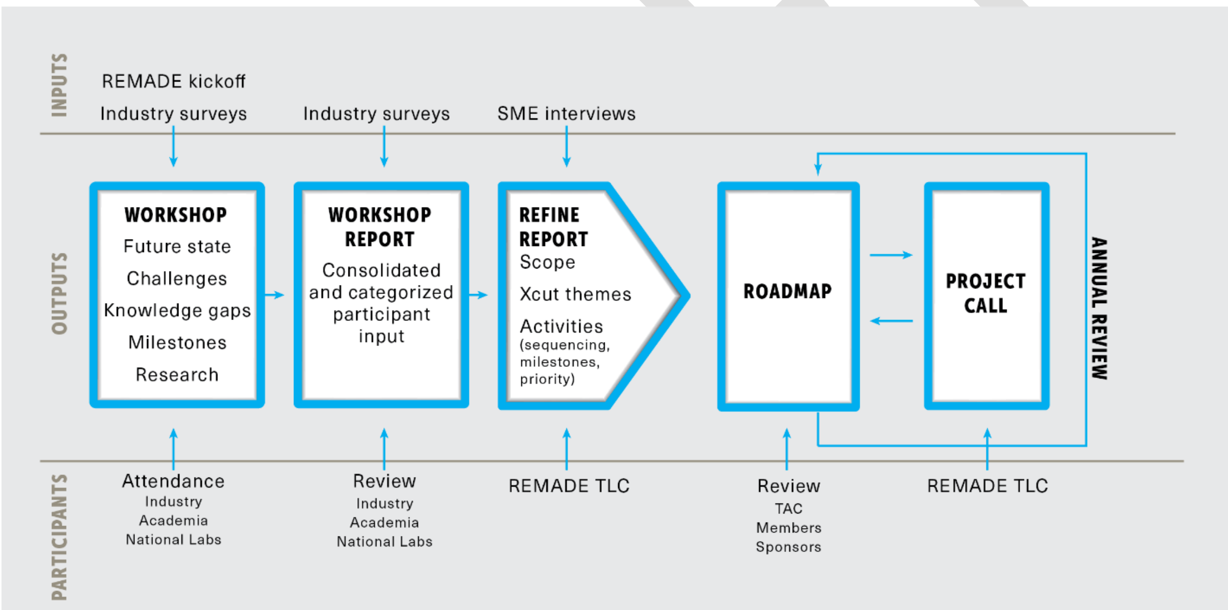
ABOUT THIS DOCUMENT

The REMADE Institute—a Manufacturing USA Institute co-funded by the U.S. Department of Energy (DOE)—was established to enable early-stage applied research and development of technologies to reduce embodied energy and carbon emissions associated with industrial-scale manufacturing. Recognizing that direct engagement with industry stakeholders is critical to setting the Institute's technology priorities and to help define REMADE's research priorities, the Institute partnered with Nexight Group, a technical and management consultancy specializing in technology roadmapping, to assist in building this roadmap.

The development of the 2018 REMADE roadmap was informed by a variety of stakeholder inputs from academia, industry, trade associations, and government, beginning with online surveys and interviews and followed by an expert workshop held in September 2017. A detailed discussion of the entire roadmap development process, summarized in Figure 1 below, may be found in *Appendix A: Development of the REMADE Institute Technology Roadmap*.

Figure 1. Roadmap development process



The results of that workshop—coupled with additional expert interviews and a high-level review of other relevant roadmaps (see *Appendix C: Relevant References*)—created the foundation for this roadmap, which is divided into the following sections:

- **Executive Summary –** This section provides an overview of the REMADE Institute and its mission, goals, and performance measures, as well as an introduction to nodes and cross-cutting themes, the two ways in which the Institute has organized and integrated its research activities.

- **Node Chapters –** The work of each of the five REMADE nodes is discussed in detail in its own chapter:

  Node 1: Systems Analysis and Integration

  Node 2: Design for Re-X

  Node 3: Manufacturing Materials Optimization

  Node 4: Remanufacturing and End-of-life Reuse

  Node 5: Recycling and Recovery

  Based on the collective consensus input of the workshop participants, each chapter describes the focus of the node's work, the desired future state, the technical and economic challenges currently faced, and the knowledge gaps that must be addressed to overcome those challenges. Additionally, each chapter outlines a set of research activities and milestones needed to achieve REMADE's mission.

- **Next Steps –** Because this roadmap forecasts into the future and is meant to guide REMADE throughout its existence, it should be considered a living document that is annually re-evaluated and revised to ensure its currency and relevancy. With input from industry stakeholders and support from academic, trade association, and national partners, the Institute will revisit this roadmap annually to ensure it evolves with regard to
  - Progress or pacing of proposed activities
  - Emergence of new technologies or advancements to existing technologies
  - Changes in the U.S. manufacturing landscape

- **Appendices –** The appendices include an in-depth examination of the roadmap development process (Appendix A), as well as lists of the roadmap workshop participants and contributors (Appendix B) and relevant references (Appendix C).

EXECUTIVE SUMMARY

Background and Mission

Today, manufacturing accounts for 25 percent of U.S. energy consumption. With improvements in materials production and processing, the United States could significantly increase manufacturing energy efficiency, which could also yield substantial economic savings. To help realize these opportunities, the REMADE Institute—a $140 million Manufacturing USA Institute co-funded by the U.S. Department of Energy—was launched in January 2017.

In partnership with industry, academia, trade associations, and national laboratories, REMADE will enable early-stage applied research and development of technologies that could dramatically reduce the embodied energy and carbon emissions associated with industrial-scale materials production and processing. The REMADE Institute is particularly focused on increasing the recovery, reuse, remanufacturing, and recycling (collectively referred to as Re-X) of metals, fibers, polymers, and electronic waste.

Manufacturing
The work of the REMADE Institute is broadly focused on all material-processing industries across the entire material value chain, including production, remanufacturing, and recycling. Because of this comprehensive scope, benefits realized from the Institute's efforts may be adopted throughout the entire U.S. manufacturing landscape, rather than within only certain technology concentrations.

REMADE Institute Goals and Technical Performance Metrics (TPMs)

REMADE's early-stage applied research and development will focus on achieving the Institute goals:

- **Develop technologies capable of reducing energy emissions through a reduction in primary material consumption and an increase in secondary feedstock use in energy-intensive industries.**
- **Develop technologies capable of achieving feedstock "better than cost and energy parity" for key secondary materials.**
- **Promote widespread application of new enabling technologies across multiple industries.**

To measure progress toward these goals, the Institute has established the following TPMs:

- 30 percent reduction of primary feedstock use in manufacturing operations
- 30 percent increase in secondary feedstock use in manufacturing operations
- 30 percent increase in the recycling of specific energy-intensive materials
- 25 percent improvement in embodied energy efficiency within 5 years, and a 50 percent improvement within 10 years
- 30 percent decrease in the energy required to process secondary feedstocks within 5 years, and a 50 percent decrease within 10 years
- Secondary feedstocks at cost parity with primary feedstocks
- Reduction of primary feedstock 10 times the current use
- 20 percent decrease in emissions

REMADE Technical Focus Areas and Research Activities

What is Re-X?
Re-X is shorthand for recovery, reuse, remanufacturing, and recycling.

However, while not specifically called out in the above definition, sub-processes such as *disassembly, sorting, inspection, cleaning, and collection* should also be taken into account when considering Re-X within the manufacturing industry.

The current state of materials manufacturing technologies, tools, methods, and processes presents a number of challenges to achieving the level of Re-X envisioned as the future state of the manufacturing industry. Current products are generally not designed with Re-X in mind, and manufacturing processes are not optimized for in-plant scrap reuse or the use of lower-embodied-energy alternative feedstocks. At product end-of-life, there is a lack of reliable tools for assessing product condition and potential for Re-X, and current methods for collecting, characterizing, sorting, separating, cleaning, and reprocessing materials can make Re-X efforts too energy-intensive and cost-prohibitive.

To achieve its mission and overcome these challenges, the REMADE Institute has organized its activities around five nodes. Four nodes align to the material lifecycle stages: **Design for Re-X, Manufacturing Materials Optimization, Remanufacturing and End-of-life Reuse,** and **Recycling and Recovery**; the fifth node, **Systems Analysis and Integration**, addresses systems-level issues that are broader in scope than any one particular node and have the potential to impact all the nodes. Each node will pursue research activities focused on overcoming challenges in the following areas:

- **Systems Analysis and Integration** – Data collection, standardization, metrics, and tools for understanding material flow
- **Design for Re-X** – Development of design methodologies and tools to improve material utilization at product end-of-life
- **Manufacturing Materials Optimization** – Technologies to utilize secondary feedstocks, re-use scrap materials, and reduce in-process losses in manufacturing
- **Remanufacturing and End-of-life Reuse** – Efficient and cost-effective technologies for cleaning, component restoration, condition assessment, and reverse logistics
- **Recycling and Recovery** – Rapid gathering, identification, sorting, separation, contaminant removal, reprocessing, and disposal of manufacturing materials

The process of consolidating the research activities for each node into a technology roadmap led to two key observations:

1. Research activities fell into five cross-cutting themes:
    - **Materials Processing and Recovery Techniques** – Technologies used to manufacture, recycle, recover, and reprocess materials
    - **Characterization, Qualification, and Inspection** – Technologies used to ensure the composition, quality, and purity of feedstocks and the condition of cores and components
    - **Simulation and Engineering Analysis Tools** – Science- and engineering-based tools that inform how to most effectively manufacture, recover, reuse, remanufacture, and recycle materials

- **Value Chain Integration and Impact** – Evaluation methods to optimize material product flows, quantify energy/emissions reductions, and achieve secondary feedstock cost and energy parity
- **Workforce Development** – Training and education activities to prepare the incumbent and future workforce in REMADE-relevant technologies

2. Some research activities within a particular theme, such as cleaning, were applicable to multiple nodes.

What is a Core?
A core is a previously sold, worn, or non-functional product or module, intended for the remanufacturing process.

During reverse logistics, a core is protected, handled, and identified for remanufacturing to avoid damage and preserve its value. A core is not waste or scrap and is not intended to be reused for other purposes before remanufacturing takes place.

Although research activities will be organized by nodes, these cross-cutting themes provide a useful framework for developing the roadmap because they identify ways the nodes can work in parallel on key research priorities without duplicating effort. Moving forward, these cross-node themes will be used to ensure alignment and facilitate communication among the nodes, maximizing the impact of REMADE activities and investment and accelerating progress toward achieving REMADE's mission and goals.

These cross-cutting themes and cross-nodal linkages are illustrated in Figure 2.

Figure 2. Cross-cutting themes and cross-nodal linkages

CROSS-CUTTING THEMES

	DESIGN FOR RE-X	MANUFACTURING MATERIALS OPTIMIZATION	REMANUFACTURING AND END-OF-LIFE REUSE	RECYCLING AND RECOVERY	SYSTEMS ANALYSIS AND INTEGRATION
Materials Processing and Recovery Techniques *The technologies used to manufacture, recycle, recover, and reprocess materials*		• Process modifications for secondary feedstock (SF) * • Link SF contaminants & mfg defects * • In-plant reuse of scrap • Reduce In-process losses	• Component repair/ restoration * • Surface cleaning * • Disassembly methods	• Sorting and separation technologies • Contaminant removal * • Cleaning processes * • Complex scrap liberation • Reprocessing technologies • Increase SF w/o impacting MPs	
Characterization, Qualification, and Inspection *The technologies used to evaluate the composition, quality, purity, and efficacy of feedstocks*	• Secondary feedstock (SF) material properties (MPs) *	• SF specifications and qualification * • Real-time characterization of SFs * • Material cleanliness measurement * • Material traceability standards	• Non-destructive inspection/ evaluation • Contaminant/cleanliness measurement * • Condition assessment	• SF specifications and certification * • Sensing technologies: SF characterization * • Sensing technologies: SF cleanliness * • Sensing technologies: sorting	
Simulation and Engineering Analysis Tools *Science and Engineering-based tools that inform how to most effectively mfg, recycle, reuse, reman, and recover*	• Design for Re-X trade-off analysis * • Design for Re-X methods & tools	• Thermodynamic, kinetic, and process modeling & simulation * • Embodied energy analysis *	• Reusability/reliability assessment * • Assessment of efficiency opportunities *	• Thermodynamic modeling of material separation and recovery * • Waste logistics models • Tune primary feedstock/ scrap ratio • Design tools to ↑ MRF efficiency	• Life-cycle assessment (LCA) tools & databases * • Embodied-energy * databases
Value Chain Integration and Impact *Systems-level view of how to understand and optimize material flows, reduce energy and emissions, and achieve cost and energy parity.*	• Evaluation of design for Re-X return on investment (ROI) *	• Supply chain analysis * • Cross-industry SF utilization *	• Reverse logistics networks * • Assess core condition/ residual value	• Material collection mechanisms * • Recycling economic driver determination * • Waste stream mapping • Waste stream data sharing • Industry & SF supplier collaboration *	• Material flow analyses (MFA) & scenarios * • Techno-economic analysis of secondary material markets * • Technical performance metrics • Project impact calculation • High-impact opportunities
Workforce Development	Training and activities relevant to each of the four levels of workers the Institute will address (i.e. Pre-collegiate/Secondary, Technician/AAS, Post-Secondary STEM, and Continuing Professional Education and Certification) and each of the nodes.				

Colored asterisks indicate opportunities for cross-node coordination.

High-Priority REMADE Activities

An important part of the Institute's coordinated strategy for achieving its goals is to identify and prioritize research activities necessary to address key challenges and realize the desired future state of the industry. Each node chapter of this roadmap includes a discussion of the node's vision for its future state, key challenges to achieving that vision, a set of milestones for progressing toward that future state, as well as a comprehensive list of research activities needed to reach those milestones. These activities, mapped to the cross-cutting themes that show potential cross-nodal synergies, will guide REMADE's requests for projects, which in turn will enable the Institute to meet its TPMs.

Each node has identified a subset of their research activities that are the most impactful and therefore the highest priority for REMADE to pursue over the next five years. A summary of all the high-priority activities for all the node is illustrated in the table below.

Successfully developing new or improved technologies or processes within REMADE's high-priority activity areas will facilitate measurable progress toward the fulfillment of REMADE's goals. To remain competitive in an increasingly global ecosystem, the U.S. manufacturing industry must continue to embrace technologies and strategies for the continued advancement and adoption of Re-X in U.S. manufacturing. Through its targeted and collaborative approach, the REMADE Institute seeks to motivate the subsequent industry investments required to continue to advance Re-X research and technology and ensure widespread increases in Re-X across U.S. manufacturing.

LEGEND

Nodes

Node 1: Systems Analysis and Integration

Node 2: Design for Re-X

Node 3: Manufacturing Materials Optimization

Node 4: Remanufacturing and End-of-life Reuse

Node 5: Recycling and Recovery

Cross-Cutting Themes

Materials Processing and Recovery Techniques

Characterization, Qualification, and Inspection

Simulation and Engineering Analysis Tools

Value Chain Integration and Impact

Workforce Development

2018

Establish a consistent methodology for calculating the TPMs, identify the material flow and embodied energy data required to make these calculations, and clarify where there are gaps in data or tool capabilities necessary to evaluate the TPMs
Develop an initial analysis method to calculate energy, emissions, and feedstock impacts for each REMADE Institute project
Conduct an analysis of the greatest opportunities to meet the TPMs, which TPMs will be most difficult to meet, and why. Identify prioritized list of topics for REMADE to pursue in years 2 to 5 to meet the TPMs

- Identify industry-relevant design for Re-X methodologies and identify the key metrics that should be used in the evaluation
- Quantify in-process losses (e.g., melting losses in foundries) and conduct research to minimize losses for select industries with high energy consumption
- Characterize and quantify the differences between primary and secondary materials to understand the resulting impact on manufacturing conversion and physical properties
- Quantify cost drivers for using secondary materials to identify the highest impact areas for lowering manufacturing costs
- Evaluate effectiveness of technologies for identifying latent faults associated with mechanical defects in printed circuit boards (PCBs)
- Explore novel non-destructive evaluation (NDE) assessment methods and analysis techniques for identifying damage in metals
- Improve understanding and viability of existing technology to sort metals, reduce contamination of paper, and separate polymers and e-waste

2019

- Translate methodology for evaluating the TPMs into a simple tool for measuring impact and analyze its use against ongoing REMADE projects
- Develop a system level model for tracking secondary material flows that incorporates commodity price data, and identify opportunities to optimize the management of secondary material flows
- Complete a systems analysis case study on a material of high relevance to REMADE, either due to its high embodied energy, and/or its potential for substantial energy savings
- Develop innovative new methods for design for Re-X that improve upon existing methods to enable more energy-efficient and cost-effective Re-X and demonstrate they can be used to evaluate designs
- Develop cost-effective and accurate measurement methods for in-situ sampling of metal compositions (e.g., in-situ spectral analysis technique) to enable real-time characterization of chemical composition in molten metal processing
- Conduct defect analysis to relate material composition to formation of defects (e.g., porosity, cracks, streaking in casting) to better understand root causes and inform process adjustments
- Improve measurement of thermal properties (e.g., thermal conductivity, specific heat, convection coefficients) as a function of temperature to improve simulation accuracy
- Develop method for automated fault finding of mechanical defects in PCB
- Conduct stakeholder analyses to identify best practices for Re-X outreach and education campaigns targeted at the general public, specific vendors, and end users for metals, e-waste, paper, and polymers

2020

- Integrate materials flow analysis (MFA)/lifecycle assessment (LCA) tools that have been developed and data that has been collected with existing/emerging design tools
- Refine techno-economic models to validate current approaches to achieving technology/project cost parity for the four REMADE material classes
- Conduct network analysis for a manufacturing sector of high relevance to REMADE that illustrates its entire supply chain, highlighting the best opportunities for additional efficiency gains in the system
- Utilize design for Re-X tools to identify alternative design approaches, (product configuration, material choice, component forming process, assembly technology, etc.) that enable more cost effective and profitable Re-X tradeoffs

- Develop process technologies to accommodate secondary feedstock variations
- Develop automated approaches for assessing/inspecting condition of cores (products returned for manufacturing) and components (individual parts within the core)
- Develop in-process method for NDE of as-sprayed thermal coatings
- Identify and develop deconstructive depolymerization processes for cost-effectively separating complex polymers into higher-purity monomers and oligomers, resulting in higher-value materials
- Develop and improve technologies to identify and simultaneously sort non-ferrous metal scrap
- Develop cost-effective, robust characterization methods for assessing and standardizing the composition and quality of secondary material streams by material or application

2021

- Complete integrated assessment of multiple REMADE technologies (across and within nodes) to account for combined impact of individual projects and reflect the interrelated supply chains associated with materials manufacturing
- Integrate design for Re-X tool with computer-aided design (CAD) systems and required databases to give immediate feedback to designers on potential costs and difficulties of various Re-X options (e.g., downstream tradeoffs when combining certain materials, conflicts between design and secondary materials properties)
- Develop materials that are more tolerant of unavoidable process variables and variations in secondary feedstock composition and morphology to reduce defects and scrap
- Develop machine-learning tools and techniques that enable real-time process adjustments to accommodate the materials variations typically seen in secondary feedstocks
- Enhance processes for the separation and liberation of materials at multiple length scales, including liberation of materials in multi-component complex scrap and low-cost separation technologies for complex mixed material streams (e.g., components that are part metal and part plastic)
- Evaluate e-waste management approaches nationwide to identify best practices, including those for addressing environmental, health, and safety considerations and advancements (e.g., handling and storage of batteries and toxic entities)

2022

- Final LCA tool available, together with guidance for REMADE members on selecting the most appropriate methodologies and datasets when assessing the energy implications of new and existing products or processes
- Evaluate increased filling of high-embodied-energy materials (e.g., aluminum, magnesium, polymers) with secondary feedstocks and alternative fillers to reduce embodied energy and/or weight
- Improve Municipal Solid Waste (MSW) Systems (recyclables, garbage, collection, reverse logistics) to improve recycling and recovery of high-volume landfill items
- Demonstrate processes that improve MSW recycling and recovery of high-volume landfill items

2023+

- Develop an increased understanding of and capabilities for producing functionally gradient materials with reduced embodied energy
- Implement e-waste management approaches for appropriately and safely handling the hazardous materials found in e-waste

NODE CHAPTERS

The work of each of the five REMADE Institute nodes is discussed in detail in the following five node chapters. Each chapter describes the focus of the node's work, the desired future state, the technical and economic challenges currently faced, and the knowledge gaps that must be addressed to overcome those challenges. Additionally, each chapter includes a table of research activities and milestones for 2018–2023+ that are needed to achieve the REMADE Institute's mission.

NODE 1: SYSTEMS ANALYSIS & INTEGRATION

Systems analysis and integration tools can help analyze the various stages of the material lifecycle to identify opportunities for reducing embodied energy and emissions associated with materials production and processing that are broader than any one node and therefore impact multiple nodes. However, existing tools for materials flow and lifecycle characterization have gaps in key areas due to insufficient data and little integration between disparate technologies and data sources. To close these gaps and enable industry-wide coordination and assessment, the REMADE Systems Analysis and Integration Node is focused on improving data collection, metrics and measurement, standardization, and tools for understanding material flow throughout the other four REMADE nodes (Design for Re-X, Manufacturing Materials Optimization, Remanufacturing and End-of-life Reuse, and Recycling and Recovery).

Desired Future State of the Industry

To enable improved systems analysis and integration for Re-X, the manufacturing industry must work toward achieving the following future state characteristics:

- Consistent methodologies (standards and protocols) for evaluating the lifecycle impact of end-of-life Re-X processes have been developed.
- Lifecycle assessment (LCA) databases incorporate these key end-of-life processes, include validated/verified U.S. data, and are up to date.
- Tools for evaluating U.S. manufacturing energy and emissions include end-of-life processes.
- Methods/tools for analyzing material flows through supply chains incorporate data on secondary material flows and the import/export of materials.
- The functionality of lifecycle impact and material flow methods have been extended to include economic and market considerations, enabling industry to conduct trade-off analyses and calculate return on investment for Re-X projects, supporting decision-making and planning.
- Ideally, tools for evaluating the impact of technology projects are accessible to industry, either as standalone modules or as packages integrated into existing engineering analysis tools such as computer-aided design (CAD)/computer-aided manufacturing (CAM).

Technical and Economic Challenges and Associated Knowledge Gaps

To realize the desired future state of Re-X systems analysis and integration, the manufacturing industry must work to overcome the following challenges and address the associated knowledge gaps, which are listed below each challenge.

1. **Current methods for assessing lifecycle impact have not adequately addressed market and economic considerations**
   - No integrated tools are available that allow consideration of impact and cost at the same time (i.e., LCA tools focus on impact while lifecycle cost analysis tools focus on economics).

2. **Insufficient or inadequate data on the energy and emissions impact from material and process selection**
   - LCA data on manufacturing processes is limited, often outdated, and not U.S.-specific (data is often generated in Europe).
   - LCA databases with information on energy requirements related to material production mostly cover primary materials, with little information distinguishing the energy requirements for secondary material processing.
   - LCA data on secondary processes is largely limited to broad material groups (e.g., for metals, data only covers a fraction of the alloys currently being recycled) and selected processes and often does not cover the entire processing sequence.
   - Limited understanding of the material flows associated with manufacturing makes it difficult to put specific energy savings into perspective.
   - Limited information about yield efficiencies in material and production increase uncertainty of modeling approaches.

3. **Inadequate mechanisms for identifying opportunities for cross-industry secondary feedstock utilization**
   - There is no easily accessible database available covering U.S. manufacturing that systematically includes the material requirements (inputs) and material discards (outputs) at the firm level.[1]
   - There is insufficient understanding of the complexities of U.S. manufacturing supply chain networks (a particular challenge for electronics, which has a deep supply chain).
   - There is insufficient understanding of the secondary material markets.

4. **It is difficult to provide guidance and strategic focus for REMADE research efforts because existing LCA and MFA information tends to focus on specific materials or processes, and system interactions are only partially understood**
   - No comprehensive overview is available on quantities and types of materials employed in U.S. manufacturing, which limits the ability to set priorities.
   - There is limited understanding of the trade-off effects that material selections may cause across different sectors.

REMADE Systems Analysis & Integration Research Priorities

Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced systems analysis and integration tools, technologies, and

[1] The existing industry attempt to provide such a platform is still in its infancy (i.e., Materials Marketplace) but could be used as a starting point for REMADE.

techniques. The following table outlines key systems analysis and integration research activities for REMADE to pursue over the next 10 years, focusing initially on the first five.

LEGEND

○ High-Priority Activity

Cross-Cutting Themes

- Materials Processing and Recovery Techniques
- Characterization, Qualification, and Inspection
- Simulation and Engineering Analysis Tools
- Value Chain Integration and Impact
- Workforce Development

Cross-Cutting Theme	High-Priority	SYSTEMS ANALYSIS & INTEGRATION RESEARCH ACTIVITIES	MILESTONE
Simulation and Engineering Analysis Tools	○	Establish a consistent methodology for calculating the TPMs, identify the material flow and embodied energy data required to make these calculations, and clarify where there are gaps in data or tool capabilities necessary to evaluate the TPMs	**2018** Strategy for measuring and meeting the TPMs completed, as well as a high-level analysis of the greatest opportunities to meeting the TPMs
Simulation and Engineering Analysis Tools	○	Develop an initial analysis method to calculate energy, emissions, and feedstock impacts for each REMADE Institute project	
Simulation and Engineering Analysis Tools		Develop a data collection template and guidance that REMADE members can use to evaluate material and energy efficiency for ongoing REMADE Institute projects	
Value Chain Integration and Impact	○	Conduct an analysis of the greatest opportunities to meet the TPMs, which TPMs will be most difficult to meet, and why. Identify prioritized list of topics for REMADE to pursue in years 2 to 5 to meet the TPMs	
Simulation and Engineering Analysis Tools	○	Translate methodology for evaluating the TPMs into a simple tool for measuring impact and analyze its use against ongoing REMADE projects	**2019** Data and analysis tools for tracking progress against REMADE TPMs have been consolidated/connected
Simulation and Engineering Analysis Tools		Collect the most relevant missing data required to calculate TPMs and, where appropriate, develop a method to link this data with existing databases	
Simulation and Engineering Analysis Tools		Identify the data needs for the Design for Re-X node and develop a strategy for linking this data to existing design tools or design tools under development	
Value Chain Integration and Impact	○	Develop a system level model for tracking secondary material flows that incorporates commodity price data, and identify opportunities to optimize the management of secondary material flows	
Value Chain Integration and Impact	○	Complete a systems analysis case study on a material of high relevance to REMADE, either due to its high embodied energy, and/or its potential for substantial energy savings	
Value Chain Integration and Impact		Perform an initial techno-economic analysis to assess barriers to achieving cost and energy parity for the four REMADE material classes	
Value Chain Integration and Impact		Characterize and quantify material cycles for the main REMADE material classes at national level, and identify what embodied energy data exist for each material class	
Simulation and Engineering Analysis Tools	○	Integrate MFA/LCA tools that have been developed and data that has been collected with existing/emerging design tools	**2020** Supply chain of a manufacturing sector of high
Simulation and Engineering Analysis Tools	○	Refine techno-economic models to validate current approaches to achieving technology/project cost parity for the four REMADE material classes	

SYSTEMS ANALYSIS & INTEGRATION RESEARCH ACTIVITIES	MILESTONE
Conduct network analysis for a manufacturing sector of high relevance to REMADE that illustrates its entire supply chain, highlighting the best opportunities for additional efficiency gains in the system	relevance to REMADE is well characterized, and first REMADE Institute-wide roll up of progress against the TPMs conducted
Create a structured set of industry-based scenario analysis descriptions to increase the accuracy and relevance of system level models and to help validate progress toward meeting REMADE TPMs	
Complete integrated assessment of multiple REMADE technologies (across and within nodes) to account for combined impact of individual projects and reflect the interrelated supply chains associated with materials manufacturing	**2021** First trade-off analysis of REMADE technologies completed that informs future strategy and sets the framework for similar studies of other REMADE technologies
Final LCA tool available, together with guidance for REMADE members on selecting the most appropriate methodologies and datasets when assessing the energy implications of new and existing products or processes	**2022** LCA tool in place that allows REMADE members to evaluate the material and energy efficiency of their products and processes, and demonstrated available applications
Continue refining techno-economic models aimed at achieving technology cost parity for the four REMADE material classes based on feedback received on previous projects	

NODE 2: DESIGN FOR RECOVERY, REUSE, REMANUFACTURING, & RECYCLING (RE-X)

The ability to recover, reuse, remanufacture, or recycle components depends heavily on how those components are designed. However, end-of-life Re-X is often not considered until most fundamental design decisions—such as materials selection and component structure—have already been made, which limits Re-X potential. Current design tools are also unable to simultaneously consider the desired performance characteristics and the impact on end-of-life Re-X. To address this need, the REMADE Design for Re-X Node is focused on identifying design for Re-X methods and translating them into usable tools or modules that will allow designers to assess tradeoffs and evaluate the impact that design choices have on materials Re-X at product end-of-life, ultimately enabling the design of high-performance products with improved materials utilization.

Desired Future State of the Industry

To enable increased utilization of design for Re-X approaches, the manufacturing industry must work toward achieving the following future state characteristics:

- Established methodologies exist for assessing the extent to which a design enables Re-X at end-of-life.
- Standards have been developed that enable designers to quantify the costs and benefits of Re-X characteristics in their designs.
- Product designers have access to a suite of interoperable tools and capabilities they can use to evaluate designs choices, estimate cost and benefit tradeoffs, and assess risks across a product's lifecycle.
- Manufacturers consider end-of-life costs and benefits during product design and development, routinely considering a product's future beyond its first product life.
- Designers and managers can evaluate the financial implications of design for Re-X decisions, enabling them to make more compelling business cases for considering Re-X during design.

Technical and Economic Challenges and Associated Knowledge Gaps

To realize the desired future state of design for Re-X, the manufacturing industry must work to overcome the following challenges and address the associated knowledge gaps, which are listed below each challenge.

1. Design specifications do not incorporate factors known to impact Re-X

- Industry design for Re-X standards that explicitly identify which factors to include or not to include do not exist.
- Current design for Re-X tools require too much time on the part of designers to provide initial inputs. Tools that require less time are needed.
- Current design for Re-X tools provide output that may be outside of the designer's area of expertise, leading to inaccurate analysis or improper design for Re-X decisions.

2. **Timeframe for return on investment does not account for when and what Re-X benefits will be realized**
    - Accounting methods or management systems that balance a product's expected life and the time horizon for return on investment are not available.
    - Design decision criteria do not permit economic and technical tradeoffs that occur at different points in time (first few years after product launch vs. end-of-first-life).
    - Business models for Re-X do not make their way into preliminary product conceptualization.
3. **Designers are hesitant to specify secondary feedstocks because material property data is frequently not available or incomplete, and material quality specifications are not well defined**
    - Industry-wide material property and material quality specifications for secondary feedstocks are frequently not available.
    - Designers are unsure how material property and material quality specifications for secondary feedstocks may need to be defined differently.
4. **Design and analysis methods and tools do not address the complexities required to adequately evaluate design for Re-X tradeoffs, assess risks, or address potential business implications**
    - Designers, who are familiar with making cost, performance, and quality trade-offs, do not understand or have adequate training and tools to evaluate design for Re-X tradeoffs and the associated risks.
    - Expert knowledge about what specific steps or decisions designers should make in particular situations is limited. As a result, existing design for Re-X checklists too often state the obvious ("Have you considered a more recyclable material? How you considered a reversible assembly technology?").
    - Designers do not have appropriate understanding for how to decide on the best set of design for Re-X tradeoffs on the Pareto optimal frontier.

REMADE Design for Re-X Research Priorities

Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced design for Re-X tools, technologies, and techniques. The following table outlines key design for Re-X research activities for REMADE to pursue over the next 10 years, focusing initially on the first five.

LEGEND

○ High-Priority Activity

Cross-Cutting Themes

- Materials Processing and Recovery Techniques
- Characterization, Qualification, and Inspection
- Simulation and Engineering Analysis Tools
- Value Chain Integration and Impact
- Workforce Development

Theme	High-Priority	DESIGN FOR RE-X RESEARCH ACTIVITIES	MILESTONE
Simulation and Engineering Analysis Tools	○	Identify industry-relevant design for Re-X methodologies and identify the key metrics that should be used in the evaluation	**2018** Existing methods for design for Re-X and metrics by which to evaluate designs have been identified and documented
Workforce Development		Work with REMADE partners to develop a roadmap for preparing the future workforce to utilize design for Re-X approaches	
Simulation and Engineering Analysis Tools		Establish centralized, living (curated and maintained) design for Re-X portal that includes industry-specific best practices, describes design for Re-X evaluation methods, and provides links to existing tools and ROI details	**2019** A design for Re-X methodology and metrics by which to evaluate designs have been developed Demonstrate methods for evaluating design for Re-X potential on industry-relevant designs
Simulation and Engineering Analysis Tools		Develop initial design for Re-X standards to formalize how to quantify the extent to which a design enables Re-X at end-of-life	
Value Chain Integration and Impact	○	Develop innovative new methods for design for Re-X that improve upon existing methods to enable more energy-efficient and cost-effective Re-X and demonstrate they can be used to evaluate designs	
Simulation and Engineering Analysis Tools	○	Utilize design for Re-X tools to identify alternative design approaches, (product configuration, material choice, component forming process, assembly technology, etc.) that enable more cost-effective and profitable Re-X tradeoffs	**2020** Design tool prototype developed that links design decisions' impacts to first use, end-of-life, and subsequent lifecycles Industry standard worker training established for design for Re-X
Simulation and Engineering Analysis Tools		Develop stand-alone design for Re-X prototype tool(s) that integrate with required databases to evaluate designs	
Value Chain Integration and Impact		Develop methods and metrics that quantify the long-term costs and benefits of Re-X during design and overcome limitations imposed by short-term ROI calculations	
Workforce Development		Develop industry short course and professional development programs for training managers, designers, and others in design for Re-X according to agreed-upon best practices (e.g., Six Sigma model)	
Workforce Development		Develop and deliver new university courses (e.g., mechanical engineering and materials science design programs) on design for Re-X that incorporate industry-relevant considerations	
Simulation and Engineering Analysis Tools	○	Integrate design for Re-X tool with CAD systems and required databases to give immediate feedback to designers on potential costs and difficulties of various Re-X options (e.g., downstream tradeoffs when combining certain materials, conflicts between design and secondary materials properties)	**2021** Design for Re-X impacts (costs and benefits) directly integrated into CAD tools
Simulation and Engineering Analysis Tools		Investigate deep learning approaches for optimizing design for Re-X approaches	

DESIGN FOR RE-X RESEARCH ACTIVITIES	MILESTONE
Develop design business cases that account for all stakeholders along the value chain to demonstrate long-term ROI of design for Re-X and identify opportunities for sustainable new product development	
Incorporate ROI criteria into CAD-based design for Re-X design tools	**2022** Business model considerations for ROI integrated into CAD tool
Incorporate machine-learning approaches into design for Re-X framework to shorten the design for Re-X cycle time	**2023+** CAD-based tools and relevant databases integrated into publicly accessible design for Re-X systems

NODE 3: MANUFACTURING MATERIALS OPTIMIZATION

Optimizing the use of materials in manufacturing depends on the ability to control materials properties, improve process efficiency, and increase the use of more cost-effective alternative feedstocks without sacrificing desired materials performance. By developing and implementing tools, technologies, and methods that facilitate more precise control of materials manufacturing, manufacturers can process secondary feedstocks at cost and energy parity with primary feedstocks and improve manufacturing yields for primary feedstocks, thereby decreasing the embodied energy in materials manufacturing. To realize these benefits, the REMADE Manufacturing and Materials Optimization Node is focused on advancing technologies and processes to increase the use of secondary feedstocks and decrease the consumption of primary feedstocks by reusing scrap materials and reducing in-process losses in manufacturing.

Desired Future State of the Industry

To reduce energy and emissions through optimizing primary and secondary material utilization during manufacturing, the manufacturing industry must work toward achieving the following future state characteristics:

- New process technologies that consume less energy during manufacturing are available.
- Manufacturers consume less primary feedstock at the factory level by reusing scrap materials, reducing in-process losses, and increasing production yields.
- High-quality, cost-competitive secondary feedstocks are readily available and used in place of primary feedstocks.
- Improved or alternative manufacturing processes and technologies can make real-time adjustments to better accommodate materials or chemistry variations and/or alternative feedstocks.
- Advanced simulation and optimization tools are available for utilizing primary and secondary feedstocks in manufacturing.
- Processes are available for cross-industry utilization of secondary feedstocks.

Technical and Economic Challenges and Associated Knowledge Gaps

To realize the desired future state of manufacturing materials optimization, the manufacturing industry must work to overcome the following challenges and address the associated knowledge gaps, which are listed below each challenge.

1. **Secondary feedstock materials are less attractive to manufacturers because they exhibit greater compositional and material property variance, as well as higher production losses, compared with virgin materials**
   - Manufacturing processes developed for primary feedstock are unable to tolerate chemistry variations frequently seen in secondary feedstock.
   - Manufacturing processes are not usually developed to make real-time adjustments to process parameters to accommodate variations in secondary feedstock.

- The ability to use secondary feedstock without adversely impacting properties (e.g., plastic/polymer colors) is limited.
- Standards for recertifying secondary feedstock across materials sources have not been developed for many materials.

2. **Difficulty characterizing and evaluating material composition in real time**
    - Techniques for real-time characterization of materials during manufacturing and reprocessing are either too expensive or lack the required resolution.
    - Quantitative quality analyses that links trace contaminant levels in secondary feedstock to material property variations are not available.
    - Real-time sensing techniques and analysis capabilities for correction of molten metal quality are not available for production environments.
    - Industry-wide standards/mechanisms that permit material traceability for secondary feedstock have not been widely accepted and implemented.

3. **High cost and complexity of using secondary feedstocks in manufacturing processes limits their use**
    - Low-cost methods for material cleaning, separation, and sorting of secondary feedstock are not available.
    - There is an inability to handle iron and other impurities in secondary feedstock use with newer aluminum alloys (e.g., aluminum-lithium in aerospace).
    - No technology exists for copper removal and alloy separation from automotive scrap, which limits secondary reuse.

4. **Inherent materials waste from current manufacturing processes is not being effectively utilized to produce secondary feedstocks**
    - Understanding, data, and education regarding the potential benefits and impact of cross-industry use of waste streams is limited.
    - There is limited industry awareness that waste products with materials properties comparable or similar to virgin materials are a viable source of secondary feedstocks.
    - Communication and data-sharing among companies and industries on the availability and composition of waste streams is still ad hoc.
    - Technologies to use cross-industry waste are not available.

5. **Manufacturers typically focus on reducing production losses rather than decreasing embodied energy, and they may not have access to advanced technologies or tools to accomplish both**
    - Low-cost methods to increase yields and reduce in-process losses and defects are not accessible to small and medium enterprises.
    - Low-cost economical processes to manufacture net-shaped or functionally gradient materials to reduce embodied energy are not available.
    - Models for performing embodied energy analysis for materials manufacturing processes are either unavailable or limited to databases that are not widely available.

REMADE Manufacturing Materials Optimization Research Priorities

Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced tools, technologies, and processes for manufacturing materials optimization. The following table outlines key manufacturing materials optimization research activities for REMADE to pursue over the next 10 years, focusing initially on the first five.

LEGEND

○ High-Priority Activity

Cross-Cutting Themes

- Materials Processing and Recovery Techniques
- Characterization, Qualification, and Inspection
- Simulation and Engineering Analysis Tools
- Value Chain Integration and Impact
- Workforce Development

Cross-Cutting Theme	High-Priority	MANUFACTURING MATERIALS OPTIMIZATION RESEARCH ACTIVITIES	MILESTONE
Materials Processing and Recovery Techniques	○	Quantify in-process losses (e.g., melting losses in foundries) and conduct research to minimize losses for select industries with high energy consumption	**2018** Identification and quantification of the greatest opportunities for reducing embodied energy in material manufacturing
Characterization, Qualification, and Inspection	○	Characterize and quantify the differences between primary and secondary materials to understand the resulting impact on manufacturing conversion and physical properties	
Characterization, Qualification, and Inspection		Identify and benchmark available and emerging technologies for secondary stream characterization to assess cost effectiveness	
Value Chain Integration and Impact	○	Quantify cost drivers for using secondary materials to identify the highest impact areas for lowering manufacturing costs	
Characterization, Qualification, and Inspection	○	Develop cost-effective and accurate measurement methods for in-situ sampling of metal compositions (e.g., in-situ spectral analysis technique) to enable real-time characterization of chemical composition in molten metal processing	**2019** Initial assessment of the impact of chemistry variation on material efficiency
Simulation and Engineering Analysis Tools	○	Conduct defect analysis to relate material composition to formation of defects (e.g., porosity, cracks, streaking in castings) to better understand root causes and inform process adjustments	
Simulation and Engineering Analysis Tools		Conduct thermodynamic and kinetic modeling and validation of material manufacturing, especially when secondary feedstocks are used	
Value Chain Integration and Impact	○	Improve measurement of thermal properties (e.g., thermal conductivity, specific heat, convection coefficients) as a function of temperature to improve simulation accuracy	
Materials Processing and Recovery Techniques	○	Develop process technologies to accommodate secondary feedstock variations	**2020** Initial processes and sensing to accommodate chemistry variation and enable
Materials Processing and Recovery Techniques		Develop sensors coupled with technologies for real-time automated control and monitoring of key variables within a manufacturing process to minimize yield losses (e.g., melt loss in aluminum melting operations) and enable increased use of secondary feedstocks	

MANUFACTURING MATERIALS OPTIMIZATION RESEARCH ACTIVITIES	MILESTONE
Incorporate project results in undergraduate- and graduate-level courses (e.g., modules on reducing embodied energy during materials manufacturing and materials selection)	increased use of secondary feedstocks
Develop materials that are more tolerant of unavoidable process variables and variations in secondary feedstock composition and morphology to reduce defects and scrap	**2021** Demonstration of process control strategies to reduce energy and emissions and increase secondary feedstock use
Develop machine-learning tools and techniques that enable real-time process adjustments to accommodate the materials variations typically seen in secondary feedstocks	
Evaluate increased filling of high-embodied-energy materials (e.g., aluminum, magnesium, polymers) with secondary feedstocks and alternative fillers to reduce embodied energy and/or weight	**2022** Secondary feedstocks with increased tolerance to chemistry variations demonstrated
Investigate cross-industry uses of secondary feedstocks	
Develop an increased understanding of and capabilities for producing functionally gradient materials with reduced embodied energy	**2023+** Path to 30% increase in secondary feedstocks demonstrated
Demonstrate cross-industry use of feedstocks	

NODE 4: REMANUFACTURING AND END-OF-LIFE REUSE

By extending the useful life of products or components, remanufacturing and end-of-life reuse provides a significant opportunity for increasing the energy efficiency and reducing the embodied energy of materials in U.S. manufacturing. Remanufacturing and reuse of products and components retains the embodied energy of a product, including the materials and processes used to produce the product. Reuse involves identifying a market for used materials or products, and insuring that the material is in functional condition.

Given the high embodied-energy savings potential, overcoming barriers to remanufacturing and reuse of products, especially those with limited recycling pathways, will contribute to achieving REMADE Technical Performance Metrics. To facilitate increased remanufacturing and end-of-life reuse, the Remanufacturing and End-of-life Reuse Node is focused on three activities: 1) improving technologies for assessing the remaining life and residual value of products and components, 2) achieving cost parity for material reuse, and 3) developing restoration methods to restore components to "like-new" condition. Product design has a major impact on both the technical feasibility and cost effectiveness of both reuse and remanufacturing and will be approached in concert with the Design for Re-X Node.

Desired Future State of the Industry

To increase remanufacturing and end-of-life reuse, the manufacturing industry must work toward achieving the following future state characteristics:

- More cost-effective condition assessment technologies, tools, or methods are available for widespread industry use, allowing for more reliable diagnostics and assessment of damage in used components.
- Historical usage data, including extreme operating conditions, are embedded into equipment, enabling improved decision-making related to reuse and remanufacturing.
- Feasible opportunities for end-of-life reuse have been identified and pursued for a range of products that are not currently remanufactured or reused, extending the useful life of those products and components and reducing energy and emissions.
- Material efficiency and cost parity of secondary materials in remanufacturing is improved substantially through the development and dissemination of more robust and cost-effective processes, including disassembly, cleaning, restoration, and condition assessment processes.
- Known, validated, and accepted industry standards for repair of commonly used metals, plastics, and electronics are in place to ensure the reliability of remanufactured products.
- Robust reverse logistics networks allow for the efficient delivery of items for reprocessing that have reached the end of their first useful life.
- The remanufacturing process energy footprint is well understood, and approaches to significantly reduce total remanufacturing process energy have been identified.

Technical and Economic Challenges and Associated Knowledge Gaps

To realize the desired future state of remanufacturing and end-of-life reuse, the manufacturing industry must work to overcome the following challenges and address the associated knowledge gaps, which are listed below each challenge.

1. **Lack of robust non-destructive inspection/evaluation techniques for assessing damage limit opportunities to remanufacture or reuse components**
   - Assessing the condition of materials is critical in remanufacturing to ensure that remanufactured components have like-new performance; however, while there are methods to detect cracks in metal, no methods exist to measure accumulated mechanical damage (e.g., fatigue) prior to crack development.
   - Methods are not available to assess the condition of solid state components and microprocessors in electronics.
   - In practice, while used circuit boards are functionally tested for condition assessment, there are no technologies available to measure or detect latent defects in used printed circuit boards.

2. **There are limited techniques for translating inspection/evaluation data into an assessment of residual value and remaining life of products and components.**
   - Most end-of-life products do not have any associated usage or operational data, making it difficult to assess core value and predict remaining life of components.
   - Existing technologies for assessing core condition or value prior to disassembly are based on limited data and limited understanding of condition beyond the external appearance.
   - Many remanufacturers do not have access to or awareness of methods for determining the useful life of products or components.

3. **The costs of labor and key remanufacturing processes, such a component repair, limit reuse yield and remanufacturing intensity.**
   - Off-line process monitoring and associated defects affect the cost-effectiveness of thermal spray coating repairs, but there are currently no methods for in-process monitoring of the quality of the coating in terms of bonding strength and coating properties.
   - Data to quantify which remanufacturing process areas offer the greatest opportunity for improvement of remanufacturing process energy efficiency is frequently not available. While proprietary data on material reuse yields and overall cost-effectiveness may exist, this data has not been consolidated into an accessible and actionable format to inform research priorities.
   - Quantitative methods for assessing contamination/cleanliness levels for components are not cost-effective or capable of handling production volumes required by remanufacturers, limiting the ability to optimize cleaning processes for used components.
   - Analysis models and accelerated testing methods for validation of component repairs are extremely limited.

4. **Methods for restoring components to “like-new” condition are not available, limiting the ability to reuse components in remanufacturing**
   - There are no cost-effective technologies for removing the conformal coating or potting from circuit boards, limiting the ability to repair and reuse circuit boards.
   - While light scratches can be polished, there are no cost-effective methods for repairing deeper damage to plastic surfaces.

5. **Inefficiencies in the collection of end-of-life products limits cross-industry and cross-product reuse**
    - Because remanufacturing and reuse-related businesses require reliable sources of used or end-of-life products, new cost-effective approaches for establishing effective reverse logistics networks for new product lines are needed.

REMADE Remanufacturing and End-of-life Reuse Research Priorities

Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced remanufacturing and end-of-life reuse tools, technologies, and techniques. The following table outlines key remanufacturing and end-of-life reuse research activities for REMADE to pursue over the next 10 years, focusing initially on the first five.

LEGEND

○ High-Priority Activity

Cross-Cutting Themes

Materials Processing and Recovery Techniques; Characterization, Qualification, and Inspection; Simulation and Engineering Analysis Tools; Value Chain Integration and Impact; Workforce Development

Cross-Cutting Theme	High-Priority	REMANUFACTURING AND END-OF-LIFE REUSE RESEARCH ACTIVITIES	MILESTONE
Characterization, Qualification, and Inspection	○	Evaluate effectiveness of technologies for identifying latent faults associated with mechanical defects in printed circuit boards (PCBs)	**2018** Identify methods to find damage in components
Characterization, Qualification, and Inspection	○	Explore novel non-destructive evaluation (NDE) assessment methods and analysis techniques for identifying damage in metals	
Workforce Development		Develop training modules on basic remanufacturing processes (e.g., cleaning, repair, condition assessment) to support workforce development outreach	
Materials Processing and Recovery Techniques		Develop models and proof-of-concept system for selection of intelligent cleaning processes	**2019** Complete proof-of-concept experiments for initial remanufacturing and reuse projects
Materials Processing and Recovery Techniques		Develop techniques for decomposition/removal of potting material from PCB	
Characterization, Qualification, and Inspection	○	Develop method for automated fault finding of mechanical defects in PCB	
Characterization, Qualification, and Inspection		Develop NDE method and analysis techniques for fatigue assessment in metals	
Value Chain Integration and Impact		Assess the energy, labor, and waste generation footprint of remanufacturing processes in different industry sectors to identify process and energy efficiency opportunities	
Workforce Development		Compile existing data on cleaning processes to develop training materials and disseminate best practices to industry	
Materials Processing and Recovery Techniques		Develop processes for repair of damage to plastic components	**2020** Identify inspection technologies applicable to cores and remanufacturing process technologies
Characterization, Qualification, and Inspection	○	Develop automated approaches for assessing/inspecting condition of cores (products returned for remanufacturing) and components (individual parts within the core)	
Characterization, Qualification, and Inspection	○	Develop in-process method for NDE of as-sprayed thermal coatings	

REMANUFACTURING AND END-OF-LIFE REUSE RESEARCH ACTIVITIES	MILESTONE
Develop in-situ method or embedded sensor for tracking mechanical fatigue in products Develop framework for assessing reuse of electrical components and chips on PCBs Work with community colleges and other nodes to develop Re-X training	
Develop improved processes and engineering procedures for repairing damage in metals Develop system for PCB reuse/remanufacturing decision support Identify/assess opportunities to reuse/remanufacture consumer products Gather existing data on repair processes, develop training materials, and disseminate best practices	**2021** Identify approaches for achieving cost parity of remanufacturing relative to new products
Develop lower-energy-intensity process alternatives for energy intensive processes Integrate REMADE technologies to demonstrate proof-of-concept for consumer product remanufacturing	**2022** Demonstrate potential to achieve 30% improvement in remanufacturing process energy intensity, and remanufacturing process technologies for 1–2 selected consumer products
Develop methods to assess degradation in solid-state components	**2023+**

NODE 5: RECYCLING & RECOVERY

Recovering and recycling end-of-life materials offers the potential to divert manufacturing waste streams and obtain secondary materials without the costs, embodied energy, and emissions resulting from extracting and processing virgin feedstock. However, due to the technical and logistical challenges associated with collecting, characterizing, sorting, separating, cleaning, and reprocessing materials, recycling and recovery today can often be energy-intensive and cost-prohibitive, with the cost of recycling sometimes exceeding the value of secondary products or the cost of virgin materials. To address these issues, the REMADE Recycling and Recovery Node is focused on developing and advancing methods and technologies for the rapid gathering, identification, sorting, separation, contaminant removal, reprocessing, and disposal of high-scrap materials (fibers, metals, polymers, and e-waste).

Desired Future State of the Industry

To enable increased recycling and recovery, the manufacturing industry must work toward achieving the following future state characteristics:

- Industry is able to rapidly and efficiently collect, characterize, physically sort, separate, and clean recycled materials and produce secondary feedstock at cost parity with primary materials.
- New markets exist with a stable demand for secondary materials that significantly reduces landfilled waste.
- Improved supply chain logistics optimize the flow of scrap and recycled materials to minimize transportation, reduce costs, and meet customer demand for specific materials.

Technical and Economic Challenges and Associated Knowledge Gaps

To realize the desired future state of recycling and recovery, the manufacturing industry must work to overcome the following challenges and address the associated knowledge gaps, which are listed below each challenge.

1. **High cost of secondary feedstock materials limits attractiveness as replacement for primary feedstocks**
   - Current technologies for processing and recovering recycled materials at appropriate quality levels are too expensive for large-scale commercial implementation.
   - Critical economic drivers for the recycling industry have not been delineated or incorporated into viable models.
   - Impacts of logistics and quality on recycling are not well known.
   - Required material specifications are not well known or standardized to enable consistent secondary feedstock production that can meet user needs.
   - Cleaning processes for materials are not well known or standardized to utilize best practices and environmentally friendly formulations to achieve needed objectives for secondary feedstocks.

2. **Existing reverse logistics networks for recycling and recovery are not well established, which limits the ability to collect and separate waste streams**
   - Logistics models to integrate waste generation with waste processing in economic configurations are inadequate.

- Cross-business collaboration mechanisms to improve recycling and secondary feedstock utilization are not well established.
- Current collection mechanisms are unable to capture all valuable recyclables from complex waste streams.
- Tools to help design more efficient “dirty” material recovery facilities (MRFs) that capture recyclables from garbage streams need to be improved and more broadly utilized.

3. **Current cross-industry communication regarding quality and availability of waste streams and secondary feedstocks limits recycling and recovery and increases costs**
    - Business collaboration between the waste generation industry and secondary feedstock suppliers is limited.
    - Potential integration of downstream users of secondary feedstock materials with waste generators and recyclers is not well understood or utilized.

4. **Technologies for cleaning and characterizing materials are either ineffective, which degrades the value of the scrap and can lead to secondary feedstock variations, or too expensive, which limits the amount of material that can be recycled or recovered economically**
    - Cost-effective sensors that enable more effective cleaning and characterization to facilitate secondary feedstock production and quality are needed.
    - Improved methods for identification and removal of hazardous materials from waste streams are needed.
    - Cost-effective technologies for removal of trace contaminants that achieve the required level of cleanliness are not available, resulting in lower-quality secondary feedstocks.
    - Improved liberation and separation technologies are needed.
    - Leveraging learning from other fields (e.g., artificial intelligence, Materials Genome Initiative, the Internet-of-Things) is needed to help increase recycling rates and availability of secondary feedstocks.

5. **Technologies for sorting and separating materials are either ineffective, which limits the scrap to lower-quality and lower-value markets, or too expensive, which limits the amount of material that can be recycled or recovered economically**
    - Low-cost separation methods that meet the needs of large-volume markets with highly specific specifications and recycling environments are needed.

REMADE Recycling & Recovery Research Priorities

Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced tools, technologies, and processes for recycling and recovery. The following table outlines key recycling and recovery research activities for REMADE to pursue over the next 10 years, focusing initially on the first five.

LEGEND

○ High-Priority Activity

Cross-Cutting Themes

- Materials Processing and Recovery Techniques
- Characterization, Qualification, and Inspection
- Simulation and Engineering Analysis Tools
- Value Chain Integration and Impact
- Workforce Development

RECYCLING AND RECOVERY RESEARCH ACTIVITIES	Cross-Cutting Theme	High-Priority	MILESTONE
Improve understanding and viability of existing technology to sort metals, reduce contamination of paper, and separate polymers and e-waste	Value Chain Integration and Impact	○	**2018** Develop prioritized list of materials and processes to enable greater potential secondary feedstock streams
Evaluate cost-effective opportunities for automation of materials stream sorting	Value Chain Integration and Impact		
Survey industry to identify additional markets and applications for currently recycled materials (e.g., polymers and plastics)	Value Chain Integration and Impact		
Quantify the impact of contamination on single-stream recycling facilities	Value Chain Integration and Impact		
Develop and improve technologies to increase secondary feedstock use for high-value applications in industries/material types (e.g., metals, e-waste, paper, and polymers) where little or no secondary feedstock is currently used	Materials Processing and Recovery Techniques		**2019** Complete initial sorting and characterization tasks Provide initial offerings of enhanced educational programs
Demonstrate recovered polymers can be utilized for secondary feedstocks in injection molding	Materials Processing and Recovery Techniques		
Identify cost-effective, environmentally friendly methods for material cleaning (e.g., oil removal)	Materials Processing and Recovery Techniques		
Develop recycling analysis tools to support optimization of capital investment and the overall cost of doing business, coupled with the layout and design of sorting and physical separation processes to reduce embodied energy and increase value recovery	Simulation and Engineering Analysis Tools		
Conduct stakeholder analyses to identify best practices for Re-X outreach and education campaigns targeted at the general public, specific vendors, and end users for metals, e-waste, paper, and polymers	Workforce Development	○	
Enhance existing Re-X educational programs to provide the most current industry views on approaches to recycling processes	Workforce Development		
Identify and develop deconstructive depolymerization processes for cost-effectively separating complex polymers into higher-purity monomers and oligomers, resulting in higher-value materials	Materials Processing and Recovery Techniques	○	**2020** Demonstrate effective materials liberation techniques at bench scale Show effectiveness of virtual and augmented reality techniques
Develop and improve technologies to identify and simultaneously sort non-ferrous metal scrap	Materials Processing and Recovery Techniques	○	
Develop cost-effective, robust characterization methods for assessing and standardizing the composition and quality of secondary material streams by material or application	Characterization, Qualification, and Inspection	○	
Utilize virtual and augmented reality training opportunities for next-generation industry workers to enhance process efficiencies for metals, e-waste, paper, and polymers	Workforce Development		

RECYCLING AND RECOVERY RESEARCH ACTIVITIES	MILESTONE
● Enhance processes for the separation and liberation of materials at multiple length scales, including liberation of materials in multi-component complex scrap and low-cost separation technologies for complex mixed materials streams (e.g., components that are part metal and part plastic)	**2021** Complete work with MRFs and other stakeholders that clearly shows implementation of enhanced sorting methods, etc.
Develop higher-quality (i.e., trace-level contaminants, high molecular purity) recycled material feedstocks that can be produced more cost effectively	
● Evaluate e-waste management approaches nationwide to identify best practices, including those for addressing environmental, health, and safety considerations and advancements (e.g., handling and storage of batteries and toxic entities)	
Develop and improve technologies that use less energy and allow for increased selectivity	**2022** Completed network/supply chain analysis of key manufacturing sector in terms of its use of all REMADE materials
● Improve Municipal Solid Waste (MSW) Systems (recyclables, garbage, collection, reverse logistics) to improve recycling and recovery of high-volume landfill items	
● Demonstrate processes that improve MSW recycling and recovery of high-volume landfill items	
● Implement e-waste management approaches for handling the hazardous materials found in e-waste appropriately and safely	**2023+** Markets for materials have been developed and show that more energy has been saved by implementation of program

NEXT STEPS

In 2018, REMADE will begin implementing the research priorities outlined in this roadmap via requests for projects (RFPs) and a project selection process designed to align member needs with Institute research and development efforts. The funded projects will represent the most impactful development opportunities that will ultimately motivate subsequent industry investments required to improve Re-X across the U.S. manufacturing ecosystem.

Because the roadmap is a forward-looking document meant to guide the REMADE Institute throughout its existence, the Institute will update its roadmap annually, in accordance with REMADE's Operational Plan. REMADE will continuously measure progress toward achieving its goals, adjusting its priorities and expanding its available resources to maximize the impacts of its efforts.

Specifically, as part of the 2018 update, the REMADE TLC will conduct the following activities:

- Conduct more extensive interviews with each REMADE member, as well as organizations interested in joining REMADE to refine the roadmap priorities
- Seek to align research activities more closely with each of the Institute's TPMs
- Gather additional benchmarking information to help prioritize those activities that will yield the greatest impact consistent with the Institute's goals and mission and the priorities of REMADE's members

Annual updates will also be critical to ensure that the REMADE roadmap evolves with the changing landscape of U.S. manufacturing, including the advancement of existing manufacturing technologies and processes, the availability of new technologies, and shifting and emerging manufacturing needs and opportunities.

APPENDIX A: DEVELOPMENT OF THE REMADE INSTITUTE TECHNOLOGY ROADMAP

The REMADE Institute Technology Roadmap, as well as the topics for REMADE's first Project Call, was developed using a multi-step process coordinated by the REMADE Institute's Technical Leadership Committee (TLC). The key component of this process was a three-day Technology Roadmap Workshop—held September 18–20, 2017 in Rochester, NY and facilitated by Nexight Group—that included participants from industry, academia, national laboratories, and trade associations. The results of this workshop were coupled with additional inputs from surveys, subject matter expert interviews, and other relevant documents, including existing roadmaps. At various points during the roadmapping process, workshop participants, the TLC, and the Department of Energy-Advanced Manufacturing Office (DOE-AMO) reviewed the workshop report and intermediate roadmap drafts prepared by the TLC and Nexight to further refine the content.

Activities Prior to the Technology Roadmap Workshop

Development of the REMADE Institute Roadmap began with an August 2016 proposal workshop held in Denver, CO. At this workshop, participants from industry, academia, national laboratories, and trade associations identified key challenges preventing achievement of the technical performance metrics (TPMs) outlined in the REMADE Institute Funding Opportunity Announcement (FOA). Later, at the REMADE Institute Kick-off Meeting held June 19–20, 2017 in Rochester, NY, participants attended break-out sessions that were organized by nodes to review the barriers from the August 2016 workshop and identify additional technical barriers.

Online Surveys

Based on the inputs from the June workshop, the TLC developed four online surveys aligned to the four stages of the material lifecycle: design, manufacturing, remanufacturing and end-of-life reuse, and recycling and recovery. These surveys were sent to both industry stakeholders who had been involved with the original REMADE proposal as well as those who had not. In each survey, participants were asked to identify, from a broad list, the key barrier impacting their industry, as well as provide additional information about which REMADE-relevant material classes this barrier impacted, and whether the impact was financial or technical. Because the surveys were developed using the Crowdoscope collective intelligence tool, participants were also able to review and anonymously comment on responses from other participants. Initial survey participation in advance of the technology roadmapping workshop was limited, however, due to the limited time between the dates of the surveys' release and the workshop.

The results of these surveys were reviewed during the first day of the September technology roadmapping workshop. Participants who had not yet taken the survey had an opportunity to complete it, and all results were reviewed on the second day of the workshop to inform discussions. To collect additional input, the survey was kept open for 10 days following the workshop, during which time workshop participants and trade associations helped to disseminate the survey to an even broader audience. By the time the survey closed on September 30, 2017, 157 participants had responded.

Technology Roadmapping Workshop

The technology roadmapping workshop was held on September 18–20, 2017. The first day of the workshop was limited to industry and trade association participants and members of the TLC, who presented an overview of the technology landscape relevant to REMADE, as well as initial survey results. Participants then divided into break-out sessions aligned to the four material lifecycle stages (design, manufacturing, remanufacturing and end-of-life reuse, and recycling and recovery) to define the desired future state of the industry and potential milestones by which the Institute could measure progress.

On the second day, industry and trade association participants identified and prioritized the technical and economic challenges preventing industry from achieving the desire future state and delineated the initial knowledge gaps associated with each challenge. University and national lab participants later joined the industry participants to further discuss and refine these technology and economic challenges. All the participants worked collectively to more comprehensively identify all the underlying knowledge gaps for each technical and economic challenge, which they then categorized and prioritized. On the last day of the workshop, the participants identified research activities that could address the knowledge gaps.

Workshop Report

Following the workshop, Nexight Group prepared a summary report of the key findings, as well as the desired future state, technical and economic challenges, knowledge gaps, and research activities identified at the workshop. This report, which contained the raw, unfiltered voting data from the workshop, was provided to all the workshop participants and the TLC, who were asked to review the report and provide feedback to ensure it accurately captured workshop discussions.

Preparation of the REMADE Institute Technology Roadmap

In addition to editing the workshop report for clarity, the TLC worked with Nexight to identify topics (e.g., pulp and paper industry) that had not been adequately addressed at the workshop due to lack of specific industry participation. The TLC identified and interviewed subject matter experts from the pulp and paper industry to ensure roadmap content encompassed the needs of this sector.

Additionally, the TLC and Nexight Group worked together to

1. Remove topics that were outside the scope of REMADE
2. Realign topics identified during the workshop from one node to another more appropriate node when needed
3. Clarify wording when the language around the desired future state, challenges, or knowledge gaps did not sufficiently reflect the technical inputs gathered during the workshop
4. Develop an initial list of cross-cutting themes to help identify potential linkages among activities across the nodes, as well as avoid duplication of effort

The TLC prioritized the list of research activities for each node that had been developed during the roadmapping workshop, identifying activities that would best enable REMADE to achieve its TPMs and deliver impact to U.S. manufacturers. To maximize potential benefit to manufacturers, as part of this effort, industry input was prioritized over that of universities and national labs. The research activities were then organized into a logical sequence of activities by year and the level of difficulty involved in conducting the research. In cases where there were gaps between the various activities, the TLC identified necessary intermediate research required and incorporated these additional activities into the timeline, which also included refined milestones for each node based on the initial milestones developed by the workshop participants.

Using the information collected during the workshop and synthesized by the TLC, Nexight Group compiled an initial draft of the roadmap which was reviewed by the TLC and key DOE-AMO staff. Based on input from AMO and subsequent edits by the TLC, additional roadmap versions were developed and iterated on with the AMO and the TLC, leading to a draft public version of the roadmap that was provided to both workshop participants and members of REMADE's Technical Advisory Committee (TAC) for comment. Based on their feedback, a final draft of REMADE's Technology Roadmap was published.

Development of the First Project Call

In parallel with the development of the technology roadmap, topics for the first project call were identified and prioritized using the process outlined in Figure 1 in the *About This Document* section of the roadmap. While recruiting potential REMADE Institute members, interviews with companies identified additional research priorities that those companies were interested in pursuing. To remain true to the feedback collected during the roadmap workshop and recognizing that the timing of the workshop prevented broader industry participation, this feedback was generalized to enable broader participation by organizations that possessed the requisite expertise and were interested in developing proposals.

APPENDIX B: ROADMAP WORKSHOP PARTICIPANTS AND CONTRIBUTORS

** = workshop participant*

Name	Organization
Magdi Azer *	REMADE Institute (*Chief Technology Officer*)
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APPENDIX C: RELEVANT REFERENCES

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