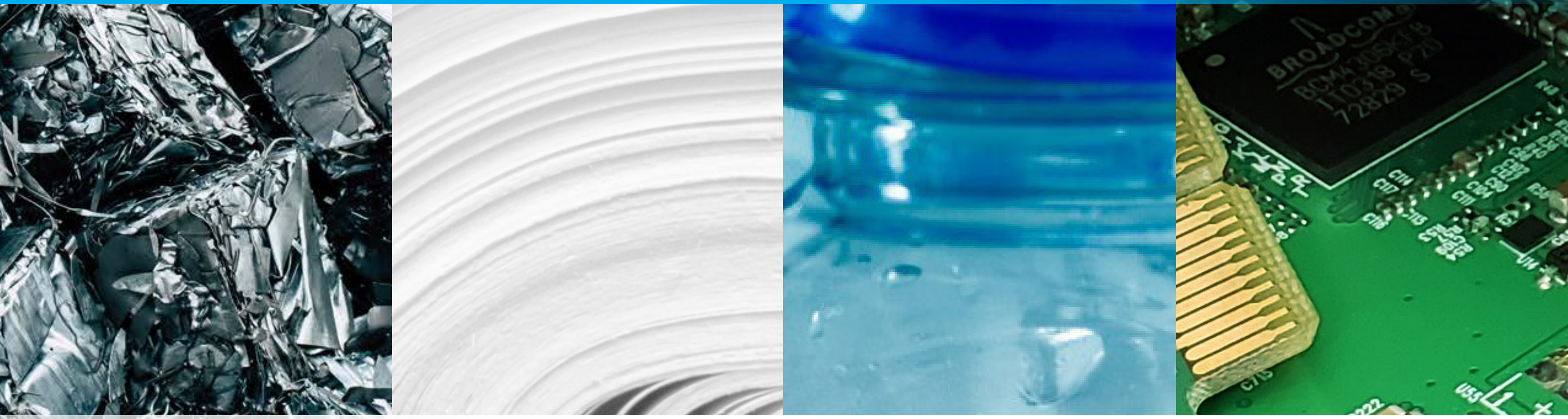
REMADE Institute
Technology Roadmap 2020



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Acknowledgement and Disclaimer

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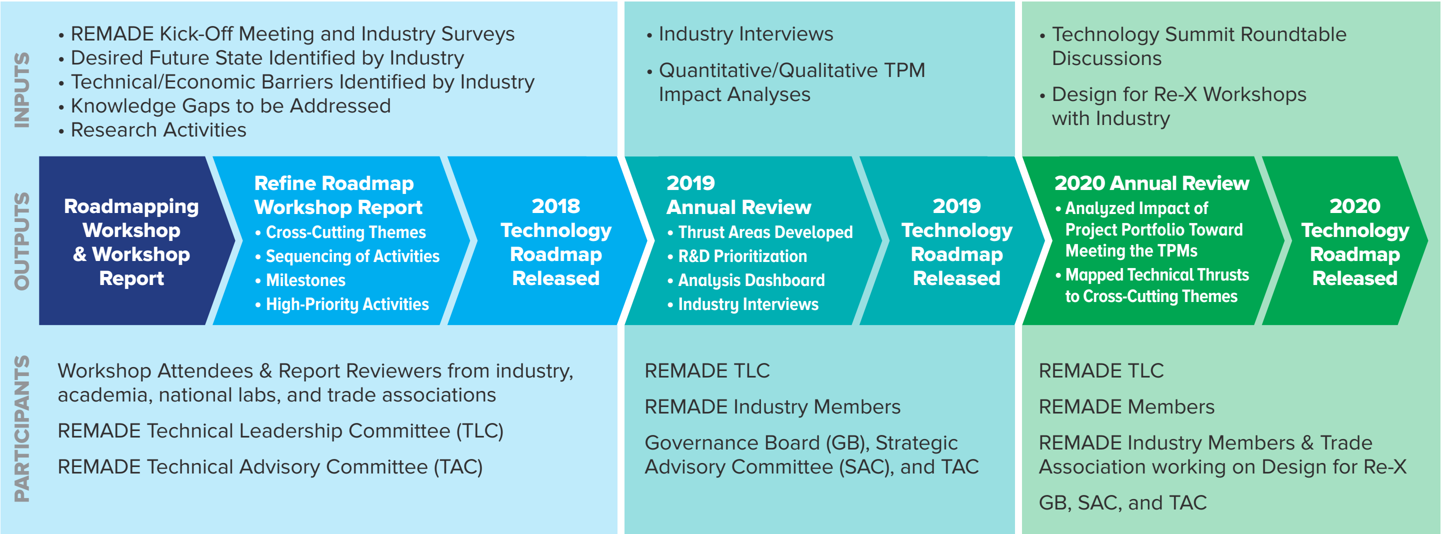
About This Document

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. In partnership with its Members and in collaboration with the Department of Energy, the REMADE Institute focuses on driving down the cost of technologies needed to reuse, remanufacture, and recycle materials such as metals, fibers, polymers, and electronic waste and aims to achieve a 50 percent improvement in embodied energy efficiency by 2027.

The 2020 REMADE Technology Roadmap represents the third iteration of this roadmap. To develop the initial Technology Roadmap that was released in 2018, the REMADE Institute partnered with the Nexight Group, a technical and management consultancy specializing in technology roadmapping. Recognizing that direct engagement with industry stakeholders was critical to establishing the REMADE Institute's technology priorities and to help define its research priorities, the REMADE Institute held a technology roadmapping workshop in September 2017. Augmented by a series of interviews and online surveys, this workshop brought together subject matter experts from academia, industry, the national laboratories, and trade associations. The results of that workshop—coupled with additional expert interviews and a review of other relevant roadmaps— enabled the REMADE Institute to develop this Technology Roadmap and created the foundation for the 2019 and 2020 REMADE Technology Roadmap updates. The inputs, outputs, and participants who contributed to the development of these three roadmaps is summarized in Figure 1 below.

Figure 1: Technology Roadmap Development Process



INPUTS	• REMADE Kick-Off Meeting and Industry Surveys • Desired Future State Identified by Industry • Technical/Economic Barriers Identified by Industry • Knowledge Gaps to be Addressed • Research Activities	• Industry Interviews • Quantitative/Qualitative TPM Impact Analyses	• Technology Summit Roundtable Discussions • Design for Re-X Workshops with Industry
OUTPUTS	**Roadmapping Workshop & Workshop Report** **Refine Roadmap Workshop Report** • Cross-Cutting Themes • Sequencing of Activities • Milestones • High-Priority Activities **2018 Technology Roadmap Released**	**2019 Annual Review** • Thrust Areas Developed • R&D Prioritization • Analysis Dashboard • Industry Interviews **2019 Technology Roadmap Released**	**2020 Annual Review** • Analyzed Impact of Project Portfolio Toward Meeting the TPMs • Mapped Technical Thrusts to Cross-Cutting Themes **2020 Technology Roadmap Released**
PARTICIPANTS	Workshop Attendees & Report Reviewers from industry, academia, national labs, and trade associations REMADE Technical Leadership Committee (TLC) REMADE Technical Advisory Committee (TAC)	REMADE TLC REMADE Industry Members Governance Board (GB), Strategic Advisory Committee (SAC), and TAC	REMADE TLC REMADE Members REMADE Industry Members & Trade Association working on Design for Re-X GB, SAC, and TAC

A detailed discussion of the 2018 Technology Roadmap development process, the 2019 Technology Roadmap update, and the technology roadmap contributors can be found in *Appendix A: Development of the 2018 REMADE Institute Technology Roadmap*, *Appendix B: 2019 REMADE Institute Technology Roadmap Update*, and *Appendix C: Technology Roadmap Contributors*, respectively.

2020 Technology Roadmap Update

The 2020 Technology Roadmap has been updated by the TLC using the process summarized in Figure 1, which included the following actions: 1) Analysis of REMADE project portfolio to identify gaps in coverage by material class and focus area, 2) Quantitative analysis to evaluate progress toward meeting the REMADE Technical Performance Metrics (TPMs)[1] for embodied energy, primary and secondary feedstock consumption, and emissions, 3) Virtual break-out sessions that were held for each focus area during the 2020 Technology Summit to validate the status of previously identified high-priority research activities and identify new high-priority topics that should be added to the Technology Roadmap, 4) Design for Re-X discussions held with industry and trade association Members to identify which design topics REMADE should address, and 5) Feedback provided by REMADE's Technical Advisory Committee (TAC), Strategic Advisory Committee (SAC), and Governance Board (GB). Like prior iterations of the REMADE Technology Roadmap, the 2020 Technology Roadmap Update was used to identify the research priorities for each Node in REMADE's fourth Request for Proposals (RFPs).

The revised and updated 2020 Technology Roadmap is divided into the following sections:

▶ Introduction

This section provides an overview of the REMADE Institute and its mission, goals, and Technical Performance Metrics. It also introduces the Nodes (focus areas) for the REMADE Institute and Technical Thrust Areas—the two approaches by which the Institute has organized and integrated its research activities. These technical thrusts, high priority research activities, and research activities are also mapped to the Cross-cutting Themes that were included in the original 2018 Technology Roadmap.

▶ Node Chapters

The work of each of the five REMADE Nodes (Focus Areas) is discussed in detail in their respective chapters.

Systems Analysis & Integration

Design for Reuse, Remanufacturing, Recovery, & Recycling (Re-X)

Manufacturing Materials Optimization

Remanufacturing & End-of-Life Reuse

Recycling and Recovery

Based on the collective consensus input of the original workshop participants, subsequent feedback collected through interviews with industry Members, and break-out sessions held at the 2020 REMADE Technology Summit, each chapter describes the focus of the Node's work, the desired future state identified by industry, the technical and economic challenges industry currently faces, and the knowledge gaps that must be addressed to overcome those challenges. Each chapter also outlines the research activities for each Technical Thrust Area that are needed to achieve REMADE's mission.

To ensure that REMADE's research portfolio is positioned to deliver the greatest impact for its Members and achieve the REMADE Institute TPMs, each research activity in the roadmap has been evaluated based on three criteria: 1) *Impact versus the TPMs*, 2) *Importance to REMADE's Research Portfolio* and 3) *Probability of Success*. These criteria were also used to identify which research activities would be designated as "high-priority" in the 2019 and the 2020 Technology Roadmaps[2].

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[1] Additional information regarding the TPMs can be found in *Appendix D: Technical Performance Metrics*.

[2] Additional details regarding these evaluation criteria are provided in Appendix E: Research Portfolio Impact Analysis and Prioritization Methodology.

High Priority REMADE Activities

Within each Node chapter, the REMADE Institute has identified “high-priority” research activities, which are a subset of research activities deemed to be the most impactful/important activities REMADE should pursue over its five years of federal funding. These “high-priority” activities have been consolidated into this single section and are organized by Technical Thrust Area.

Next Steps

Because this 2020 Technology Roadmap update is a forecast and is meant to guide REMADE throughout its existence, it should be considered a living document that is regularly re-evaluated and revised to ensure its currency and relevancy. With input from industry stakeholders and support from academic, trade association, and national laboratory partners, the REMADE Institute will revisit this Technology Roadmap annually to ensure it evolves based on the following considerations:

- Progress or pacing of proposed activities
- Emergence of innovative technologies or advancements to existing technologies
- Changes in the U.S. manufacturing landscape

Appendices

The appendices include additional information regarding the following topics that are relevant to the Technology Roadmap, including:

- Development of the REMADE Institute Technology Roadmap (Appendix A)
- 2019 Technology Roadmap Update (Appendix B)
- Technology Roadmap Contributors (Appendix C)
- Technical Performance Metrics (TPMs) (Appendix D)
- Research Portfolio Impact Analysis and Prioritization Methodology (E)
- Industry Member Interviews (Appendix F)
- Evalutation of Research Activity Impacts (Appendix G)
- Relevant References (Appendix H)

Introduction

Background, Mission, & Goals

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.

The **Mission** of the REMADE Institute is to enable the early stage applied research and development (R&D) of key industrial platform technologies that could dramatically reduce the embodied energy and carbon emissions associated with industrial-scale materials production and processing.

In partnership with industry, academia, national laboratories, and trade associations, REMADE is particularly focused on increasing the reuse, remanufacturing, recovery, and recycling (collectively referred to as Re-X) of metals, fibers, polymers, and electronic waste (e-waste).

By eliminating and/or mitigating the technical and economic barriers that prevent greater material reuse, remanufacturing, recovery, and recycling (Re-X), the REMADE Institute seeks to motivate the subsequent industry investments that will be required to complete technology development and deploy these technologies across the U.S. manufacturing ecosystem.

The primary **goals** of the REMADE Institute are to

1. Reduce energy use and emissions by decreasing primary material use in energy-intensive industries;
2. Replace primary feedstock materials through increased use of secondary feedstocks;
3. Achieve better than cost and energy parity between primary and secondary feedstocks; and
4. Develop transformational technologies to expand material reuse, remanufacturing, recovery, and recycling.

To measure progress towards these goals and guide the research agenda, the REMADE Institute has established **Technical Performance Metrics (TPMs)**. Figure 2 maps the REMADE TPMs to the Institute Goals.

Manufacturing Relevance

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 sectors.

Figure 2: REMADE Institute Goals and Technical Performance Metrics (TPMs)

	↓ **30%** Primary Feedstock (FS) Consumed	↓ **30%** Secondary FS Processing Energy	↑ **25%** Embodied Energy Efficiency	↓ **20%** GHG Emissions	Cross-Industry Reuse	Cost and Energy Parity
Reduce **energy use & emissions** by **decreasing primary material use** in energy-intensive industries	✓		✓	✓		
Replace **primary feedstock materials** through **increased use of secondary feedstocks**	✓	✓				✓
Achieve **better than cost & energy parity** between secondary feedstocks & primary feedstocks			✓	✓		✓
Develop **transformational technologies** to expand material recycling, recovery reuse and remanufacturing	✓	✓	✓	✓	✓	✓

Technical Focus Areas

The current state of materials manufacturing technologies, tools, methods, and processes presents 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 secondary feedstocks. At product end-of-life, there is a lack of reliable tools for assessing product condition and the potential for Re-X. Finally, current methods for collecting, characterizing, sorting, separating, cleaning, and reprocessing materials can also make recycling too energy-intensive and cost-prohibitive.

▶ Nodes (Focus Areas)

To achieve its mission and overcome these challenges, the REMADE Institute has organized its activities around five Nodes (focus areas). Four Nodes align to the material life cycle stages: Design for Re- X, Manufacturing Materials Optimization, Remanufacturing & End-of-life Reuse, and Recycling & Recovery. The fifth Node, Systems Analysis & Integration, addresses systems-level issues that are broader in scope than any one Node and have the potential to impact all the Nodes. A brief description of each node is provided in Figure 3.

▶ Technical Thrust Areas

To communicate the work of the REMADE Institute more effectively to internal and external audiences, organize similar research activities within each Node, and coordinate research activities across the Nodes, the REMADE Institute has identified a series of Technical Thrust Areas. With assistance from the Technical Advisory Committee (TAC), the Thrust Areas have been chosen consistent with terminology that is recognized across the various industries where the REMADE Institute works. For example, two of the Thrust Areas for the Recycling & Recovery Node are Mechanical Recycling Technologies and Chemical and Solvent-Based Recycling & Separation Technologies.

Organizing activities according to Thrust Area provides two benefits to the REMADE Institute. First, it allows the REMADE Institute to prioritize similar activities with a greater degree of granularity. For example, under the Mechanical Recycling Thrust Area, one can identify all sorting-related tasks in the Technology Roadmap and prioritize the development sorting technologies for non-ferrous scrap, ferrous scrap, or multi-layer films and flexible plastic packaging based on the timing of research activities and the impact of each research activity relative to the TPMs. Second, the Thrust Areas provide the REMADE Institute a simple mechanism to identify and coordinate research activities across Nodes that are related to a particular supply/value chain. For example, to increase the recycling rate for multi-layer films and flexible plastic packaging, the REMADE Institute and its partners will need to address challenges related to design, collection, sorting, cleaning, and separation of complex material streams.

The Technical Thrust Areas within each Node and the high-priority research activities for each Thrust Area are provided in Figure 4.

Figure 3: Description of REMADE Institute Nodes

Systems Analysis & Integration

The **Systems Analysis & Integration** Node identifies strategic opportunities to reduce the embodied energy and emissions associated with materials production and processing and evaluates the economic impact of new technologies or changing demand patterns at a project, company, sector, or national level.

Manufacturing Materials Optimization

The **Manufacturing Materials Optimization** Node develops processes, sensing technologies, and simulation tools that enable manufacturers to: increase their use of secondary and cross industry feedstocks without loss of performance or properties, reuse scrap generated during manufacturing, and reduce in-process losses.

Recycling and Recovery

The **Recycling & Recovery** Node matures technologies to increase the availability of secondary feedstocks by developing tools and technologies to economically collect, recover, sort, separate, purify and reprocess metals, polymers, fibers, and e-waste.

Design for Reuse, Remanufacturing, Recovery & Recycling (Re-X)

The **Design for Re-X** Node develops application domain-specific frameworks (such as Design for Remanufacturability) and creates tools that enable design engineers to understand how their design choices will impact the ability to reuse, remanufacture, recover, or recycle products, components, and materials.

Remanufacturing & End-of-Life Reuse

The **Remanufacturing & End-of-life Reuse** Node improves technologies for characterizing the condition of products and components, identifies (the most) cost-effective approaches for core and component processing, and develops repair technologies to restore component to “like-new” condition.

Figure 4: Technical Thrust Areas for each Node and the High-priority Research Activities for each Thrust Area

Systems Analysis & Integration

- **Systems Analysis Methods, Tools, and Data**

System insights on material flows (from material flow analysis) and their embodied energy and associated emissions (from life cycle assessment) to allow the REMADE Institute to assess the impacts and opportunities associated with its research activities within and across all stages of a material's life cycle.

- **Techno-economic Analysis Models and Tools**

Techno-economic analysis models and tools to identify cost-effective strategies to increase reuse, remanufacturing, recovery, and recycling of materials within and across different industries. Relevant activities include development of modeling tools to identify and address inefficiencies in the recovery and processing of recyclables, and evaluation of the economic impact of newly developed technologies and changing demand parameters that increase the availability of secondary feedstocks.

Design for Reuse, Remanufacturing, Recovery & Recycling (Re-X)

- **Design for Re-X Assessment Frameworks**

Frameworks that address design issues that are unique to one stage of the materials life cycle, such as Design for Recycled Content, Design for Remanufacturability, or Design for Product Assembly/Disassembly. To help engineers evaluate design issues that affect multiple stages of the materials life cycle, REMADE may also develop Design for Circularity frameworks.

- **Design for Re-X Tools**

Tools to evaluate the life cycle (energy, emissions, and materials feedstocks) and financial impacts of design decisions at end of life or the tradeoffs between initial production costs and revenue streams at end-of-life. The goal of research activities in this Technical Thrust Area is to pilot Design for Re-X tools that can be integrated with CAD systems and relevant life cycle analysis databases.

Manufacturing Materials Optimization

- **Characterization, Qualification, and Simulation Technologies**

Real-time material quality measurement methods that allow manufacturers to reduce in-process losses. Simulation tools that, when coupled with manufacturing validation trials, help manufacturers identify processing approaches to increase secondary feedstock consumption.

- **Manufacturing and Process Control Technologies**

Process technologies that help manufacturers increase secondary and cross industry feedstock content without loss of performance or properties, reduce in process losses, and reuse scrap generated during manufacturing. Activities that will be pursued include adjusting processing approaches, incorporating sensing technologies that provide real-time automated control and monitoring, and developing machine learning tools and techniques to guide process development or enable real-time process adjustments.

Remanufacturing & End-of-Life Reuse

- **Robust Non-destructive Inspection/Evaluation Techniques**

Inspection and evaluation techniques that allow remanufacturers to assess damage and characterize the condition of mechanical, electrical, and electro-mechanical products and components. Technologies for assessing/inspecting the condition of cores with minimal disassembly and cleaning to enable cost-effective remanufacturing.

- **Remanufacturing Analysis Tools and Methods**

Tools and methods for assessing the residual value/remaining life of cores and identifying (the most) cost-effective approaches for core and component processing to automate fault detection associated with mechanical defects in printed circuit boards, quantify fatigue damage and assess remaining life in metal cores and components, and enable reuse of electrical components and chips on PCBs.

- **Low-cost Component Repair Technologies and Restoration Methods**

Methods that enable direct material reuse, mitigate fatigue damage in metals, and demonstrate proof of concept remanufacturing of consumer products to increase the component reuse yield and the volume of products that can be cost-effectively remanufactured.

Recycling and Recovery

- **Technologies and Tools to Increase Collection and Recovery**

Tools and technologies to minimize contamination and preserve the economic value of recyclates (from Municipal Solid Waste, automobile shredders, and other waste streams) during collection and recovery. Projects that study the logistics associated with collection and pre-processing of waste streams and identify opportunities to eliminate/minimize the impact of single stream recycling.

- **Mechanical Recycling Technologies for Sorting, Separating (physically), and Liberating (sizing) Materials**

Cost-effective sorting, separation (physical), and liberation (sizing) technologies. Sensing technologies that improve the yield and purity of waste streams, advanced separation technologies to recover polymers and metals from complex waste streams, and robotic technologies that incorporate artificial intelligence to increase sorting accuracy and throughput at MRFs.

- **Chemical and Solvent-Based Recycling and Separation (atomic/molecular) Technologies**

Purification methods to enable resin recovery, depolymerization processes for monomer recovery, and thermo-chemical conversion of polymers to chemicals, including polymeric intermediates, chemical precursors and monomers, to increase the recycling rate of polymers from textile and non-textile applications, multi-layer films and plastic packaging, and complex metal process streams.

- **Characterization, Cleaning, and Purification Technologies**

Methods to assess and standardize the composition and quality of secondary material streams and remove or neutralize the impact of residual contaminants on material properties and processing. Development of cost-effective procedures for utilizing compatibilizers to increase secondary plastic feedstocks in mixed plastics, and deinking technologies to remove water soluble inks from fibers.

Cross cutting themes provide another mechanism to highlight similar research activities and avoid duplication of efforts by multiple Nodes. The REMADE Institute has identified four cross-cutting technology themes.

These themes are as follows:

- **Materials Processing and Recovery Techniques –** Technologies used to manufacture, recycle, remanufacture, and reprocess materials
- **Characterization, Qualification, and Inspection –** Technologies used to ensure the composition, quality, and purity of feedstocks and the condition of cores[3] and components
- **Simulation and Engineering Analysis Tools –** Science- and engineering-based tools that provide guidance on how to reuse, remanufacture, recover, and recycle materials most effectively
- **Value Chain Integration and Impact –** Evaluation methods to optimize material product flows, quantify energy/emission reductions, and achieve secondary feedstock cost and energy parity

Figure 5 maps the Nodes and Technical Thrust Areas identified in Figure 4 to the Cross-Cutting Themes. The research activities listed under each Technical Thrust Area are the high-priority research activities that had previously been identified and subsequently updated as part of the 2020 Technology Roadmap Update. *Research activities that have been italicized were added to the 2020 Technology Roadmap using the process described at the beginning of this document.*

The next five chapters of this roadmap focus on the five Nodes. At the beginning of each chapter, a vision of the Node's future state identified by industry, key technical and economic challenges that must be overcome to achieve that vision, knowledge gaps, and a comprehensive list of research activities needed to realize that vision are presented. The desired future state, key technical and economic challenges, and knowledge gaps were identified during the initial REMADE Institute Technology Roadmapping Workshop in September 2017 and have been refined as part of the 2019 and 2020 Technology Roadmap updates. The research activities, which are organized by key Technology Thrust Areas, have evolved since the release of the 2018 Technology Roadmap based on changes to the project portfolio, progress versus the REMADE TPMs, and changing Member priorities. They will guide the Institute's RFP process, which in turn will enable the REMADE Institute to achieve its TPMs.

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[3] A core is a previously sold, worn, or non-functional product or module, intended for the remanufacturing process.

Figure 5: Relationship between Nodes, Technical Thrust Areas, and Cross-cutting Themes

	Materials Processing & Recovery Technologies	Characterization, Qualification & Inspection	Simulation & Engineering Analysis Tools	Value Chain Integration & Impact
Design for Re-X			**Design for Re-X Tools to Evaluate the Impact of Design Decisions on Re-X at End-of-life** • Trade-off analysis tools to compare initial production costs to end-of-life revenue streams • Tools to evaluate the life cycle and financial impacts of design decisions on end-of-life • Pilot design for Re-X tools that could integrate with CAD systems and databases	• *ID highest value product form or use of materials in products/components at end-of life* • *Tools to assess impact of design and purchasing decisions on circularity* **Design for Re-X Assessment Frameworks** • *Design for Circularity*
Manufacturing Materials Optimization	**Manufacturing/Process Control Technologies** • Increase secondary feedstock content & reuse scrap without loss of performance/properties • Processing methods to increase secondary feedstock content & reuse manufacturing scrap • Improve process yields/reduce defects when secondary feedstocks are used. • Real-time monitoring & control technologies • Machine learning tools & techniques • *Improve collection/sorting of wrought alloys*	**Characterization, Qualification, and Simulation Technologies** • Real-time material quality measurement, monitoring and control during production	• Thermodynamic & kinetic modeling tools **Design for Re-X Assessment Frameworks** • *Design for Product Assembly/Disassembly*	
Remanufacturing & End-of-life Reuse	**Low-cost Component Repair/Restoration Methods** • Proof-of-concept for consumer product remanufacturing • Methods to repair damage in metals/plastic • *Methods to mitigate metal fatigue damage* • *Methods to enable direct material reuse*	**Robust Non-destructive Inspection/Evaluation** • ID latent faults in printed circuit boards • NDE methods to assess damage in metals • In-process NDE of thermal spray coatings • Automated approaches to assess/inspect the condition of cores and components	**Remanufacturing Analysis Tools & Methods** • Automated analysis of PCB faults/defects • Metal fatigue damage/residual life analysis • Condition assessment system for PCB reuse/remanufacturing • Assess use of electrical components/chips on PCBs **Design for Re-X Assessment Frameworks** • *Design for Remanufacturing*	• Methods to enable direct reuse
Recycling & Recovery	**Technologies and Tools to Increase Collection & Recovery** • Processing approaches to minimize paper contamination during collection/recovery **Cost-effective Mechanical Recycling Technologies** • ID and sort ferrous/non-ferrous metal scrap • Sorting technologies to detect/sort mixed flexible packaging and plastic wrap at MRFs • Recovery of polymers from e-waste & ASR **Chemical & Solvent-based Recycling Technologies** • Depolymerization methods to separate complex polymers into high-purity monomers/oligomers • Depolymerization of multi-layer films and flexible plastic packaging • Chemical recycling to improve recycling rate of polymers from textiles and non-textiles • Remove pigments from polymers	**Characterization, Cleaning & Purification Technologies** • Deinking of water-soluble inks in paper • Remove residual contaminants/neutralize their effect on material properties/processes • *Standardize methods to use compatibilizers to increase secondary feedstock use* • *Enable MRFS to cost-effectively adapt to changes in waste streams composition*	• Quantify impact of single stream recycling on paper contamination • *Analysis tools to identify the most valuable end-use of a recyclable waste stream* **Design for Re-X Assessment Frameworks** • *Design for Recycled Content*	• Reverse logistics tools to increase collection, pre-processing and production of secondary feedstocks
Systems Analysis & Integration			**Systems Analysis Methods, Tools & Data** • ID greatest opportunities to meet TPMs • Develop REMADE Impact Calculator • Calculate REMADE Impacts for projects • Develop consistent methodology for calculating TPMs • Develop final LCA tools	• Material flow analyses (MFA) & scenarios **Techno-economic Analysis Models & Tools** • Systems-level techno-economic models to track secondary material flows • Optimizing mechanical/chemical recycling of PET & Polyolefins in a circular economy.

Systems Analysis & Integration

The **Systems Analysis & Integration** Node identifies strategic opportunities to reduce the embodied energy and emissions associated with materials production and processing and evaluates the economic impact of new technologies or changing demand patterns at a project, company, sector, or national level.

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 life cycle impact of end-of-life Re-X processes have been developed.
- Life cycle assessment (LCA) databases incorporate key end-of-life processes, include validated/verified U.S. data and relevant European Union (EU) 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 secondary feedstocks and scrap material import/export data in their assessments.
- Life cycle assessment and material flow methods incorporate economic and market considerations in their analysis, enabling industry to conduct trade-off analyses and calculate return on investment for Re-X projects, supporting decision-making and planning.
- Tools for evaluating the impact of technology projects are accessible to and extensively used by 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.

Insufficient or inadequate data on the energy and emissions impact from material and process selection.

- LCA data on manufacturing processes is often unavailable, outdated, or based on E.U. data (because many processes used in the EU have not been implemented in the U.S.).
- LCA databases provide energy and emissions data for primary materials, but there is limited data for secondary materials.
- 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 all the relevant processing steps.

- Limited understanding of the material flows associated with manufacturing makes it difficult to put specific energy savings into perspective.
- Yield efficiency data are frequently material-, process technology-, and/or company-specific and are not widely available, which increases the uncertainty of modeling approaches.
- There is no easily accessible database available covering U.S. manufacturing that systematically includes the material requirements (inputs) and the various material outputs at the firm level[4].
- U.S. supply chain networks are geographically dispersed, frequently reliant on overseas production (for example, electronics), and highly dependent on scrap material exports, making it difficult to understand their complexities.
- There is insufficient understanding of secondary material markets.

It is difficult to provide guidance and strategic focus for REMADE research efforts because existing LCA and materials flow analysis (MFA) information tends to focus on specific materials or processes. System interactions are not considered.

- Comprehensive overviews of the quantities and types of materials employed in U.S. manufacturing are not available, which limits the ability to set priorities.
- There is limited understanding of the trade-off effects that material selections may cause across different sectors.

Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced systems analysis and integration tools, technologies, and techniques. Table 1 outlines key **Systems Analysis & Integration** research priorities for the REMADE Institute to pursue over the next 10 years, focusing initially on the first five.

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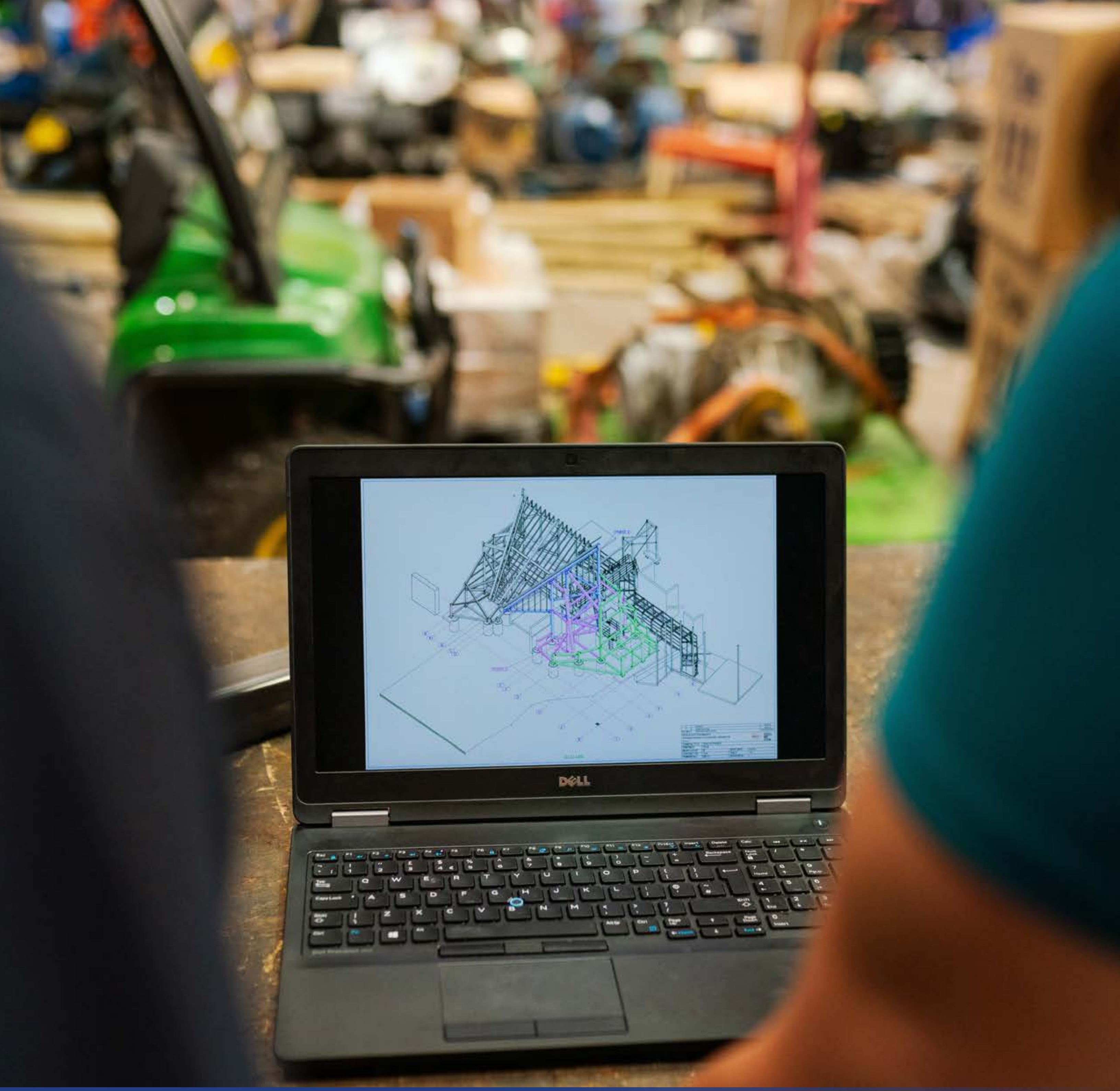
[4] The existing industry attempt to provide such a platform is still in its infancy (i.e., Materials Marketplace) but could be used as a starting point for REMADE.

Table 1: Systems Analysis & Integration Research Priorities

● **High Priority Activity**

		Probability of success	Portfolio importance	Impact
low		✦	■	✳
medium		✦✦	■■	✳✳
high		✦✦✦	■■■	✳✳✳

#	ACTIVITY DESCRIPTION	TIMELINE 2018	2019	2020	2021	2022	2023	2024	2025	PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
1	**Systems Analysis Methods, Tools and Data**											
1.01	**Conduct an analysis of the greatest opportunities to meet the TPMs, which TPMs will be most difficult to meet, and why; update list of high-priority activities for the REMADE Institute to pursue in years 2 to 5 to meet the TPMs**	🟧	🟧							✦✦✦	■■■	✳✳
1.02	**Develop an initial analysis method to calculate energy, emissions, and feedstock impacts for each REMADE Institute project**	🟧	🟧	🟧						✦✦✦	■■■	✳
1.03	Develop a data collection template and guidance that REMADE Members can use to evaluate material and energy efficiency for ongoing REMADE Institute projects	🟧	🟧							✦✦✦	■■	✳
1.04	**Translate methodology for evaluating the TPMs into a simple tool for measuring impact and analyze its use against ongoing REMADE projects**		🟧							✦✦✦	■■■	✳
1.05	Characterize and quantify material cycles for the main REMADE Institute material classes at a national level and identify what embodied energy data exists for each material class		🟧	🟧						✦✦	■■	✳✳
1.06	**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**		🟧							✦✦✦	■■■	✳✳
1.07	Collect the most relevant missing data required to calculate TPMs and, where appropriate, develop a method to link this data with existing databases		🟧	🟧	🟧					✦✦	■■	✳✳
1.08	Conduct an analysis to quantify the expected timing and quantity of waste streams that will be available for recycling (e.g., glass from solar panels or CRTs, glass from MRFs, multilayers, paper vs flexible packaging waste)				🟧	🟧				✦✦✦	■■	✳
1.09	Integrate MFA/LCA tools that have been developed and data that has been collected with existing/emerging design tools				🟧	🟧	🟧			✦	■■	✳
1.10	**Develop final LCA tool, 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**			🟧						✦✦✦	■■■	✳✳✳
2	**Techno-economic Analysis Models and Tools**											
2.01	**Conduct a systems analysis case study for PET and Olefin Polymer recycling to evaluate how to optimize mechanical and chemical recycling in pursuit of a circular economy for plastics**		🟧	🟧	🟧					✦✦	■■■	✳✳✳
2.02	Perform an initial techno-economic analysis to assess barriers to achieving cost and energy parity for the four REMADE Institute material classes			🟧	🟧	🟧				✦✦	■■	✳✳✳
2.03	**Develop a system-level techno-economic model for tracking secondary material flows to help identify and address inefficiencies in the recovery and processing of recyclables and increase the availability of secondary feedstocks**			🟧	🟧	🟧				✦✦	■■■	✳✳✳
2.04	Refine techno-economic models to validate current approaches to achieving technology/ project cost parity for the four REMADE Institute material classes				🟧	🟧	🟧			✦✦	■■■	✳✳✳
2.05	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			🟧	🟧	🟧				✦✦	■■	✳✳
2.06	Create a structured set of industry-based scenario analysis descriptions to increase the accuracy and relevance of system-level models and help validate progress toward meeting the REMADE TPMs				🟧					✦✦	■■	✳✳
2.07	Complete integrated assessment of multiple REMADE technologies (across and within Nodes) to account for the combined impact of individual projects and reflect the interrelated supply chains associated with materials manufacturing			🟧	🟧	🟧				✦✦	■■	✳✳
2.08	Continue refining techno-economic models aimed at achieving technology cost parity for the four REMADE Institute material classes based on feedback received on previous projects			🟧	🟧	🟧	🟧			✦✦	■■	✳✳
2.09	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					🟧	🟧	🟧		✦✦✦	■■	✳



Design for Reuse, Remanufacturing, Recovery, & Recycling (Re-X)

The **Design for Re-X** Node develops application domain-specific frameworks (such as Design for Remanufacturability) and creates tools that enable design engineers to understand how their design choices will impact the ability to reuse, remanufacture, recover, or recycle products, components, and materials.

Desired Future State of the Industry

To increase 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 that allow them to compare alternative design choices, estimate cost and benefit tradeoffs, and assess risks throughout a product's life cycle.
- 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 listed below each challenge.

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

- Industry design for Re-X standards that explicitly identify which factors to evaluate to increase Re-X do not exist.
- Current design for Re-X tools require too much time on the part of designers to provide initial inputs.
- 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.

Processes used to evaluate the benefits of Re-X do not encourage its adoption. Decisions regarding the economic benefits of Re-X are not made by design engineers.

- Timeframes used to calculate return on investment (the first few years after product launch) do not account for when and what Re-X benefits will be realized at end-of-life.
- Design engineers primarily focus on initial manufacturing and production costs versus the economic benefits of Re-X when they evaluate designs. Tools to help them assess the potential economic benefits of Re-X do not exist.
- Decisions regarding whether to invest in Re-X are disconnected from the design process, and may not even involve designers, making it difficult to justify investment in new design for Re-X tools.
- Business models for Re-X do not make their way into preliminary product conceptualization.

Designers are hesitant to specify secondary feedstocks because material property data is frequently not available or is incomplete. The extent to which material quality specifications should be adjusted to achieve equivalent performance is not well defined.

- Industry-wide material property and material quality specifications for secondary feedstocks are frequently not available.
- Methods to adjust material property and material quality specifications to achieve equivalent performance for secondary feedstocks are not well defined.

Design and analysis methods and tools do not address the complexities required to adequately evaluate design for Re-X trade-offs, 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 trade-offs and the associated risks.
- Expert knowledge about what specific steps or decisions designers should make to improve Re-X at end-of-life is limited and is often material-, geometry-, or product-specific, making it difficult to develop tools that can be used by multiple industries.
- Designers do not have tools for making design decisions that involve trade-offs between initial manufacturing costs and increased Re-X at end-of-life.

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. Table 2 outlines key **Design for Re-X** research priorities for the REMADE Institute to pursue over the next 10 years, focusing initially on the first five.

Table 2: Design for Re-X Research Priorities

● **High Priority Activity**

low ✦ ■ ✳
medium ✦✦ ■■ ✳✳
high ✦✦✦ ■■■ ✳✳✳

#	ACTIVITY DESCRIPTION	TIMELINE								PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
		2018	2019	2020	2021	2022	2023	2024	2025			
3	**Design for Re-X Assessment Frameworks**											
3.01	Develop a Design for Circularity Framework to help designers and purchasers evaluate the trade-offs and costs associated with different end-of-life options and their impact on circularity					█	█			✦✦	■■	✳✳
3.02	**Develop a Design for Remanufacturing Framework to help design and remanufacturing engineers evaluate the impact of design decisions on remanufacturability**			█	█	█				✦✦✦	■■■	✳✳✳
3.03	Develop a Design for Product Assembly/Disassembly Framework to help design engineers and manufacturers identify ways to increase the level of automation and minimize the labor associated with product assembly/disassembly					█	█			✦✦	■■	✳✳
3.04	Develop a Design for Recycled Content Framework to identify ways to increase the use of recycled content (secondary feedstocks) in products and ensure adequate circularity pathways and markets for these materials at end-of life				█	█				✦✦	■■	✳✳
4	**Design for Re-X Tools**											
4.01	Establish a 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 return-on-investment (ROI) details				█	█	█	█		✦✦	■■	✳✳
4.02	**Develop design for Re-X tools to evaluate the life cycle (energy, emissions, and materials/feedstocks) and financial impacts of design decisions at end-of-life**			█	█	█				✦✦✦	■■■	✳✳
4.03	**Develop analysis tools to help design engineers evaluate the trade-offs between initial production cost and the revenue stream at end-of-life**				█	█	█	█		✦✦✦	■■■	✳✳✳
4.04	**Pilot design for Re-X tools that could be integrated with CAD systems (and required databases) to provide design engineers guidance on preliminary design best practices and/or estimate the life cycle and financial impacts associated with potential Re-X design decisions**			█	█	█	█			✦✦	■■■	✳✳
4.05	Develop analysis tools to quantify the impact of design decisions on circularity					█	█	█		✦	■	✳✳
4.06	Develop analysis tools to identify the highest value product form or use of the materials in a product or component at end-of-life					█	█	█		✦	■	✳
4.07	Develop analysis tools to evaluate the impact of design decisions on remanufacturability			█	█	█				✦	■■	✳
4.08	Develop analysis tools to help purchasers evaluate the impact of potential purchasing decisions on circularity					█	█			✦✦	■	✳
4.09	Leverage recent developments in machine learning, deep learning, and generative algorithms to accelerate development of design for Re-X tools					█	█	█		✦✦✦	■■	✳✳

Manufacturing Materials Optimization

The **Manufacturing Materials Optimization** Node develops processes, sensing technologies, and simulation tools that enable manufacturers to increase their use of secondary and cross industry feedstocks without loss of performance or properties, reuse scrap generated during manufacturing, and reduce in-process losses.

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 listed below each challenge.

Secondary feedstock materials are less attractive to manufacturers because they exhibit greater compositional and material property variance. Production losses with secondary feedstocks tend to be greater than losses seen when virgin materials are used.

- Manufacturing processes developed for primary feedstock are unable to tolerate chemistry or performance variations frequently seen in secondary feedstock.
- Manufacturing processes are not typically amenable to real-time adjustments to process parameters required to accommodate variations in secondary feedstock.
- Standards for recertifying secondary feedstock across materials sources have not been developed for REMADE-relevant materials.

Techniques for characterizing and evaluating material composition in real time are limited.

- Techniques for real-time characterization of materials during manufacturing and reprocessing are either too expensive or lack the required resolution.
- Quantitative quality analyses that link 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.

Additional cost and complexity associated with using secondary feedstocks in manufacturing processes limit their use.

- Low-cost methods for cleaning, separating, and sorting secondary feedstock are not available.
- There is an inability to manage iron and other impurities in secondary feedstock for 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.

Inherent material 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 are limited.
- There is limited industry awareness that waste products with materials properties comparable 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 remains ad hoc.
- Technologies to use cross-industry waste are not available.

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.

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. Table 3 outlines key **Manufacturing Materials Optimization** research priorities for the REMADE Institute to pursue over the next 10 years, focusing initially on the first five.

Table 3: Manufacturing Materials Optimization Research Priorities

● **High Priority Activity**

low	✦	■	✳
medium	✦✦	■■	✳✳
high	✦✦✦	■■■	✳✳✳

#	ACTIVITY DESCRIPTION	TIMELINE								PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
		2018	2019	2020	2021	2022	2023	2024	2025			
5	**Characterization, Qualification, and Simulation Technologies**											
5.01	Develop cost-effective and accurate measurement methods (e.g., in-situ spectral analysis technique) to enable real-time material quality measurements and composition adjustments for secondary feedstocks				▬	▬	▬			✦✦	■■	✳✳
5.02	Develop monitoring and control technologies to improve measurement of the physical characteristics of products during papermaking to reduce product weight and end-of-line losses					▬	▬	▬		✦✦	■	✳✳
5.03	**Improve process yields and reduce defects when secondary feedstocks are used by modifying existing manufacturing processes, developing new manufacturing processes, or performing process simulations to guide process development**		▬	▬	▬	▬	▬			✦✦✦	■■	✳✳
5.04	Conduct thermodynamic and kinetic modeling (chemistry) and manufacturing validation trials to identify processing pathways to increase secondary feedstocks utilization		▬	▬	▬	▬				✦✦	■■	✳✳
6	**Manufacturing and Process Control Technologies**											
6.01	Develop processing approaches to decrease waste generation (such as slag, dust, dross, spent refractory, mold sand, etc.) and minimize yield losses associated with molten metal processing, finishing, and fabrication for the aluminum and steel industries			▬	▬	▬				✦✦✦	■	✳✳
6.02	Develop technologies for increasing kraft pulping yields in the pulp and paper industry					▬	▬	▬		✦✦	■■	✳✳✳
6.03	Develop new inks that are more easily removed during paper recycling and production			▬	▬	▬				✦✦	■■	✳✳
6.04	**Improve processing approaches to help manufacturers increase their use of secondary feedstocks without loss of properties or performance**		▬	▬	▬	▬	▬	▬		✦✦	■■■	✳✳✳
6.05	**Develop process technologies to increase secondary feedstock content and reuse scrap generated during manufacturing**		▬	▬	▬	▬	▬			✦✦	■■■	✳✳
6.06	Develop methods to cost-effectively compound recycled plastics into primary plastics				▬	▬	▬			✦✦	■■■	✳✳
6.07	**Integrate sensing technologies that provide real-time automated monitoring and control of key manufacturing process variables and equipment to minimize yield losses and enable greater use of secondary polymer, paper, and metal feedstocks**				▬	▬	▬	▬		✦✦✦	■■■	✳
6.08	Develop materials that are more tolerant of unavoidable process variables and variations in secondary feedstock composition and morphology to reduce defects and scrap		▬	▬	▬					✦	■■	✳✳
6.09	Develop machine-learning tools and techniques that enable real-time process adjustments to accommodate the materials variations typically seen in secondary feedstocks				▬	▬	▬	▬		✦✦	■■	✳✳
6.10	**Develop machine-learning tools and techniques to guide manufacturing process development or enable real-time process adjustments when using secondary or cross-industry secondary feedstocks**					▬	▬	▬		✦✦✦	■■	✳✳
6.11	Develop processing approaches to enable cross-industry uses of secondary feedstocks		▬	▬	▬	▬	▬			✦✦✦	■	✳✳✳
6.12	Improve collection and sorting of formed and wrought metal alloys (automotive market for secondary materials) to preserve their value and avoid downcycling				▬	▬	▬	▬		✦✦	■■	✳✳

Remanufacturing & End-of-life Reuse

The **Remanufacturing & End-of-life Reuse** Node improves technologies for characterizing the condition of products and components, identifies cost-effective approaches for core and component processing, and develops repair technologies to restore components to “like-new” condition.

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 and more accurate condition assessment technologies, tools, or methods to detect damage in used components are available for widespread industry use.
- Historical usage data, including exposure to extreme operating conditions, is embedded into equipment, improving decision-making related to reuse and remanufacturing.
- Feasible opportunities for end-of-life reuse have been identified and pursued for a range of products not currently remanufactured or reused.
- More robust and cost-effective disassembly, cleaning, restoration, and condition assessment processes have been developed, improving material efficiency and cost parity of secondary materials in remanufacturing.
- 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 listed below each challenge.

Lack of robust non-destructive inspection/evaluation techniques for assessing damage limit opportunities to remanufacture or reuse components.

- Although condition assessment methods to detect cracks in metal have been developed, methods to measure accumulated mechanical damage (e.g., fatigue) prior to crack development do not exist.
- Methods to assess the condition of solid-state components and microprocessors in electronics are not available.

- In practice, while used circuit boards undergo functional testing for condition assessment, there are no technologies available to measure or detect latent defects in used printed circuit boards.

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 the 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 external appearance.
- Remanufacturers do not have access to or awareness of methods for determining the useful life of products or components.

The cost of labor and key remanufacturing processes, such as component repair, limits reuse yield and remanufacturing intensity.

- There are currently no methods for in-process monitoring of the bonding strength and properties of thermal spray coating repairs, limiting their cost-effectiveness.
- Data to quantify which remanufacturing processes offer the greatest opportunity to improve energy efficiency are frequently not available or have 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 optimization of cleaning processes for used components.
- Analysis models and accelerated testing methods for validation of component repairs are extremely limited.

Methods for restoring components to "like-new" condition are not available, limiting component reuse in remanufacturing.

- There are no cost-effective technologies for removing the conformal coating or potting from circuit boards, limiting repair and reuse of circuit boards.
- While light scratches can be polished, there are no cost-effective methods for repairing deeper damage to plastic surfaces.

Inefficiencies in the collection of end-of-life products limit cross-industry and cross-product reuse.

- Remanufacturing and reuse-related businesses are not able to find reliable sources of used or end-of-life products because cost-effective approaches for establishing effective reverse logistics networks for new product lines or material reuse opportunities are not available.

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. Table 4 outlines key **Remanufacturing & End-of-life Reuse** research priorities for the REMADE Institute to pursue over the next 10 years, focusing initially on the first five.

Table 4: Remanufacturing & End-of-life Reuse Research Priorities

● **High Priority Activity**

low	✦	■	✳
medium	✦✦	■■	✳✳
high	✦✦✦	■■■	✳✳✳

#	ACTIVITY DESCRIPTION	TIMELINE								PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
		2018	2019	2020	2021	2022	2023	2024	2025			
7	**Robust Non-destructive Inspection/Evaluation Techniques**											
7.01	**Develop technologies to identify latent faults associated with mechanical defects in printed circuit boards (PCBs)**		🟦	🟦	🟦					✦✦	■■	✳✳
7.02	**Explore novel non-destructive evaluation (NDE) assessment methods for identifying damage in metals**		🟦	🟦	🟦					✦✦	■■■	✳✳
7.03	**Develop an in-process method for NDE of as-sprayed thermal coatings**			🟦	🟦					✦✦✦	■■	✳✳
7.04	**Develop automated approaches for assessing/inspecting condition of cores (products returned for remanufacturing) and components (individual parts within the core)**				🟦	🟦	🟦			✦✦	■■	✳✳✳
7.05	Develop low-cost inspection techniques to rapidly characterize contaminants and assess cleanliness of parts to be remanufactured				🟦	🟦	🟦			✦✦✦	■■	✳
7.06	Develop in situ methods or embedded sensors for tracking mechanical fatigue in products						🟦	🟦		✦✦	■■	✳
7.07	Develop methods to assess degradation in solid-state components					🟦	🟦			✦	■■	✳
8	**Remanufacturing Analysis Tools and Methods**											
8.01	**Develop automated analysis methods for finding faults associated with mechanical defects in PCBs**			🟦	🟦	🟦				✦✦	■■■	✳✳
8.02	**Develop NDE methods and analysis techniques for translating NDE data into an assessment of fatigue damage and remaining life for metals**		🟦	🟦	🟦					✦✦	■■■	✳✳
8.03	**Develop a condition assessment system for PCB reuse/remanufacturing decision support**			🟦	🟦	🟦	🟦			✦✦	■■■	✳✳
8.04	Develop decisioning systems for rapidly determining the cleaning process to minimize process development effort and process waste				🟦	🟦	🟦			✦✦	■■	✳✳
8.05	**Develop frameworks for assessing reuse of electrical components and chips on PCBs**			🟦	🟦	🟦				✦✦	■■	✳✳
9	**Develop Low-Cost Component Repair Technologies and Restoration Methods to increase the component reuse yield and volume of products that can be remanufactured**											
9.01	Develop techniques for decomposition/removal of potting material from PCBs			🟦	🟦					✦✦	■■	✳✳
9.02	Develop improved processes and engineering procedures for repairing damage in metals			🟦	🟦	🟦				✦✦	■■	✳✳
9.03	Develop processes for repair of damage to plastic components						🟦	🟦	🟦	✦✦✦	■	✳
9.04	**Integrate REMADE technologies to demonstrate proof-of-concept for consumer product remanufacturing**						🟦	🟦	🟦	✦✦	■■■	✳✳✳
9.05	**Develop methods to mitigate fatigue damage in metals**					🟦	🟦	🟦		✦✦✦	■■	✳✳
9.06	**Develop methods to enable direct material reuse**					🟦	🟦	🟦		✦✦	■■■	✳✳✳

Recycling & Recovery

The **Recycling & Recovery** Node matures technologies to increase the availability of secondary feedstocks by developing tools and technologies to economically collect, recover, sort, separate, purify and reprocess metals, polymers, fibers, 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 can rapidly and efficiently collect, characterize, physically sort, separate, and clean recycled materials and produce secondary feedstocks at cost parity with primary materials.
- Material Recovery Facilities (MRFs) can cost-effectively adapt to evolving changes in the content and volume of incoming waste streams.
- Material recyclers can respond to major disruptions in market outlets for secondary materials and cost-effectively adapt to changes in secondary material quality specifications/requirements.
- New markets with stable demand for secondary materials exist, significantly reducing the amount of waste that is landfilled.
- 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 listed below each challenge.

Added cost of using secondary feedstock materials limits their attractiveness as a replacement for primary feedstocks.

- Current technologies for processing and recovering recycled plastics, paper, and e-waste at appropriate quality levels are too expensive to warrant large-scale commercial implementation.
- Required material specifications are not clearly defined or standardized to enable consistent production of secondary feedstock that can meet users' needs.
- Where secondary materials specifications exist, the specification limits for residual contaminants may have been set in an ad hoc manner rather than relying on theoretical analysis or thorough experimental data.
- Cleaning processes needed to produce secondary feedstocks that meet customer specifications are not well known or standardized to utilize best practices and environmentally friendly formulations.

Existing reverse logistics networks for recycling and recovery are not well established for every REMADE-relevant material, 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 more efficiently and cost-effectively collect and process recyclables from mixed waste streams either do not exist or have not been broadly disseminated.

Current cross-industry communication regarding the quality and availability of waste streams and secondary feedstocks limits recycling and recovery and increases costs.

- Business collaboration between companies involved in the collection, processing, recycling, and disposal of municipal solid waste (MSW) and secondary feedstock suppliers is limited.
- Mixed waste processing facilities (MWPF), secondary feedstock suppliers, and downstream users of secondary feedstocks do not understand the benefits of collaborating or attempt to do so.

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 and would improve the production and quality of secondary feedstock are not available.
- Methods for identifying and removing hazardous materials and components (e.g., batteries in e-waste) from waste streams are not available.
- Cost-effective technologies for removal of trace contaminants that achieve the required level of cleanliness are not always available, resulting in lower recycling rates and/or lower-quality secondary feedstocks.
- Recycling companies are frequently unaware of or fail to leverage knowledge from other fields (e.g., artificial intelligence, Materials Genome Initiative, the Internet-of-Things, sensing technologies for sorting) to help them increase recycling rates and the availability of secondary feedstocks.

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.

- Cost-effective technologies for separating flexible plastic packaging and recovering polymers from e-waste are not widely available, limiting the recycling and recovery rates for these materials.

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. Table 5 outlines key **Recycling & Recovery** research priorities for the REMADE Institute to pursue over the next 10 years, focusing initially on the first five.

Table 5: Recycling & Recovery Research Priorities

● **High Priority Activity**

low ✦ ■ ✳
medium ✦✦ ■■ ✳✳
high ✦✦✦ ■■■ ✳✳✳

#	ACTIVITY DESCRIPTION	TIMELINE								PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
		2018	2019	2020	2021	2022	2023	2024	2025			
10	**Technologies and Tools to Increase Collection and Recovery**											
10.01	Develop reverse logistics tools to increase collection, preprocessing and production of secondary feedstocks		🟩	🟩	🟩					✦	■■	✳✳
10.02	**Quantify the impact of single-stream recycling on paper contamination and develop methods to eliminate/minimize this contamination**		🟩	🟩						✦✦	■■	✳✳✳
10.03	Develop processing approaches/technologies to minimize paper contamination and preserve economic value during collection and recovery of metal, polymer, and fiber waste streams				🟩	🟩				✦✦	■■	✳✳
11	**Mechanical Recycling Technologies for Sorting, Separating (physically), and Liberating (sizing) Materials**											
11.01	**Develop and improve technologies to identify and simultaneously sort ferrous and non-ferrous metal scrap**	🟩	🟩	🟩						✦✦	■■	✳✳
11.02	**Develop sorting technologies to detect and separate Mixed Flexible Packaging and Plastic Wrap at MRFs**		🟩	🟩	🟩					✦✦	■■	✳✳
11.03	**Develop cost-effective technology to recover polymers (i.e., ABS, PS, ABS/PC, and PC) from e-waste and ASR**			🟩	🟩	🟩				✦✦	■	✳✳✳
11.04	Develop cost-effective technology for separating small particle non-ferrous materials from e-waste					🟩	🟩			✦✦	■	✳✳
11.05	Develop technologies to cost-effectively liberate (size) materials in multi-component complex scrap			🟩	🟩	🟩				✦✦	■■	✳✳
11.06	Develop low-cost technologies to separate complex mixed materials streams (e.g., components that are part metal and part plastic)			🟩	🟩	🟩				✦	■■	✳✳
11.07	Develop technologies to more effectively separate different pulp grades during paper recycling					🟩	🟩			✦	■■	✳
12	**Chemical and Solvent-Based Recycling and Separation (atomic/ molecular) Technologies**											
12.01	**Identify and develop deconstructive depolymerization processes for cost-effectively separating complex polymers into higher-purity monomers and oligomers, resulting in higher-value materials**		🟩	🟩	🟩					✦✦	■■	✳✳
12.02	Increase the recycling rate of metal waste streams by identifying and developing metal molecular and atomic (metal) separation processes for cost-effectively separating complex metal process streams into higher purity metals and molecules				🟩	🟩	🟩			✦✦	■■■	✳✳
12.03	Develop depolymerization technology to increase recycling rate of multi-layer films and flexible plastic packaging		🟩	🟩	🟩					✦	■■■	✳✳
12.04	Develop chemical recycling technologies to improve the recycling rate of polymers (i.e., PET, polyolefins) for non-textile applications					🟩	🟩	🟩		✦	■■	✳✳✳
12.05	**Develop chemical recycling technologies to improve the recycling rate of polymers (i.e., PET, polyolefins) from textiles**				🟩	🟩	🟩			✦	■■	✳✳✳
12.06	**Develop chemical or solvent-based approaches for removing pigments from polymers**					🟩	🟩	🟩		✦	■■■	✳✳✳

●● **High**
●● **Priority**
Activity

low ✦ ■ ✳
medium ✦✦ ■■ ✳✳
high ✦✦✦ ■■■ ✳✳✳

#	ACTIVITY DESCRIPTION	TIMELINE								PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
		2018	2019	2020	2021	2022	2023	2024	2025			
13	**Characterization, Cleaning, and Purification Technologies**											
13.01	**Develop cost-effective, robust characterization methods for assessing and standardizing the composition and quality of secondary material streams by material or application**				🟩	🟩	🟩			✦✦✦	■■	✳✳
13.02	Develop techniques to remove residual contaminants or neutralize their effect on material properties and processing		🟩	🟩	🟩					✦✦	■■■	✳✳
13.03	Develop technologies that reduce fiber losses during repulping and fiber cleaning and separation			🟩	🟩	🟩				✦✦	■■	✳✳
13.04	**Develop deinking technologies to remove water soluble inks with minimal fiber loss**	🟩	🟩	🟩						✦✦✦	■■■	✳✳✳
13.05	Develop anaerobic processes for treating wastewater in paper recycling facilities to avoid accumulation of organic contaminants and subsequent transfer to the recycled paper						🟩	🟩		✦	■■	✳✳✳
13.06	Develop/standardize procedures for utilizing compatibilizers to increase the use of secondary plastic feedstocks in mixed plastics				🟩	🟩	🟩			✦✦✦	■■■	✳✳✳
13.07	Develop analysis tools to identify the most valuable end-use of a recyclable waste stream					🟩	🟩			✦✦	■■	✳✳
13.08	Develop methods and technologies to enable MRFs and recycling facilities to cost-effectively adapt to changes in the composition of waste streams					🟩	🟩	🟩		✦✦	■■■	✳✳✳

High-Priority REMADE Activities

High-Priority REMADE Activities

An important part of the REMADE 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.

Within each Node chapter, the REMADE Institute has identified a subset of research activities that will have the greatest impact toward achieving the TPMs and are therefore the highest priority for the REMADE Institute to pursue. These topics, identified as "high-priority" research activities* in tables 1-5 have been chosen based on input from the 2017 Technology Roadmap workshop and 2019 Technology Roadmap update, industry Member interviews, quantitative analysis of research activity impacts relative to the REMADE Institute's goals and Technical Performance Metrics (TPMs), or their importance to follow-on activities within the REMADE research portfolio. A summary of the high-priority activities for each Node is provided below.

Successfully developing innovative technologies or improving existing 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 that increase adoption of Re-X by U.S. manufacturers. Through its targeted and collaborative approach, the REMADE Institute seeks to motivate the subsequent industry investments required to continue Re-X research and technology maturation activities that will be necessary to ensure widespread adoption U.S. manufacturing.

Systems Analysis & Integration

Thrust Area: **Systems Analysis Methods, Tools, and Data**

- **Conduct an analysis** of the greatest opportunities to meet the TPMs, which TPMs will be most difficult to meet, and why; update list of high-priority activities for the REMADE Institute to pursue in years 2 to 5 to meet the TPMs
- **Develop an initial analysis method** to calculate energy, emissions, and feedstock impacts for each REMADE Institute project
- **Translate methodology** for evaluating the TPMs into a simple tool for measuring impact and analyze its use against ongoing REMADE projects
- **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 final LCA tool**, 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

Thrust Area: **Techno-economic Analysis Models and Tools**

- **Conduct a systems analysis case study** for PET and Olefin Polymer recycling to evaluate how to optimize mechanical and chemical recycling in pursuit of a circular economy for plastics
- **Develop a system-level techno-economic model** for tracking secondary material flows to help identify and address inefficiencies in the recovery and processing of recyclables and increase the availability of secondary feedstocks

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* An asterisk at the end of each research activity denotes that this it has been added to this list as part of the 2020 Technology Roadmap update.

Design for Re-X

Thrust Area: **Design for Re-X Assessment Frameworks**

- **Develop a Design for Remanufacturing Framework** to help design and remanufacturing engineers evaluate the impact of design decisions on remanufacturability*

Thrust Area: **Design for Re-X Tools**

- **Develop Design for Re-X tools** to evaluate the life cycle (energy, emissions, and materials/feedstocks) and financial impacts of design decisions at end-of-life 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 analysis tools** to help design engineers evaluate the trade-offs between initial production cost and the revenue stream at end-of-life
- **Pilot design for Re-X tools that could be integrated with CAD systems** (and required databases) to provide design engineers guidance on preliminary design best practices and/or estimate the life cycle and financial impacts associated with potential Re-X design decisions

Manufacturing Materials Optimization

Thrust Area: **Characterization, Qualification, and Simulation Technologies**

- **Improve process yields and reduce defects** when secondary feedstocks are used by modifying existing manufacturing processes, developing new manufacturing processes, or performing process simulations to guide process development

Thrust Area: **Manufacturing and Process Control Technologies**

- **Improve processing approaches** to help manufacturers increase their use of secondary feedstocks without loss of properties or performance
- **Develop process technologies** to increase secondary feedstock content and reuse scrap generated during manufacturing
- **Integrate sensing technologies** that provide real-time automated monitoring and control of key manufacturing process variables and equipment to minimize yield losses and enable greater use of secondary polymer, paper, and metal feedstocks*
- **Develop machine-learning tools and techniques** to guide manufacturing process development or enable real-time process adjustments when using secondary or cross-industry feedstocks*

[*] An asterisk at the end of each research activity denotes that this it has been added to this list as part of the 2020 Technology Roadmap update.

Remanufacturing and End-of-Life Reuse

Thrust Area: **Robust Non-destructive Inspection/Evaluation Techniques**

- **Develop technologies to identify** latent faults associated with mechanical defects in printed circuit boards (PCBs)
- **Explore novel non-destructive evaluation (NDE)** assessment methods for identifying damage in metals
- **Develop an in-process method** for NDE of as-sprayed thermal coatings
- **Develop automated approaches** for assessing/inspecting condition of cores (products returned for remanufacturing) and components (individual parts within the core)

Thrust Area: **Remanufacturing Analysis Tools and Methods**

- **Develop automated analysis methods** for finding faults associated with mechanical defects in PCBs
- **Develop NDE methods and analysis techniques** for translating NDE data into an assessment of fatigue damage and remaining life for metals
- **Develop condition assessment system** for PCB reuse/remanufacturing decision support
- **Develop frameworks** for assessing reuse of electrical components and chips on PCBs

Thrust Area: **Low-cost Component Repair Technologies and Restoration Methods**

- **Integrate REMADE technologies** to demonstrate proof-of-concept for consumer product remanufacturing
- Develop methods to **mitigate fatigue damage** in metals*
- Develop methods to **enable direct material reuse***

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* An asterisk at the end of each research activity denotes that this it has been added to this list as part of the 2020 Technology Roadmap update.

Recycling and Recovery

Thrust Area: **Technologies and Tools to Increase Collection and Recovery**

- **Quantify the impact of single-stream recycling** on paper contamination and develop methods to eliminate/minimize this contamination

Thrust Area: **Mechanical Recycling Technologies for Sorting, Separating (physically), and Liberating (sizing) Materials**

- **Develop and improve technologies** to identify and simultaneously sort ferrous and non-ferrous metal scrap
- **Develop sorting technologies** to detect and separate Mixed Flexible Packaging and Plastic Wrap at MRFs
- **Develop cost-effective technology** to recover polymers (i.e., ABS, PS, ABS/PC, and PC) from e-waste and ASR

Thrust Area: **Chemical and Solvent-Based Recycling and Separation (atomic/molecular) Technologies**

- **Identify and develop** deconstructive depolymerization processes for cost-effectively separating complex polymers into higher-purity monomers and oligomers, resulting in higher-value materials
- **Develop chemical recycling technologies** to improve the recycling rate of polymers (i.e., PET, polyolefins) for non-textile applications
- **Develop chemical recycling technologies** to improve the recycling rate of polymers (i.e., PET, polyolefins) from textiles
- **Develop chemical or solvent-based approaches** for removing pigments from polymers

Thrust Area: **Characterization, Cleaning, and Purification Technologies**

- **Develop cost-effective, robust characterization methods** for assessing and standardizing the composition and quality of secondary material streams by material or application
- **Develop deinking technologies** to remove water soluble inks with minimal fiber loss

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[*] An asterisk at the end of each research activity denotes that this it has been added to this list as part of the 2020 Technology Roadmap update.

Next Steps

The 2020 revisions improve the organization and specificity of the R&D activities, the relevance of the Technology Roadmap for identifying future RFP topics, and thus the value and implementation of the resulting projects and technologies – all in service of furthering the progress toward REMADE's TPMs and other goals.

Because the Technology Roadmap is a forward-looking document meant to guide the REMADE Institute throughout its existence, the Institute will continue to update its Technology Roadmap annually in accordance with the Institute's Operational Plan. The REMADE Institute will continuously measure progress toward achieving its goals, adjusting its priorities and expanding its available resources to maximize the impacts of its efforts. As part of future updates, the REMADE TLC will continue the following activities:

- Conduct interviews with REMADE Members to refine the Technology Roadmap priorities;
- Conduct analyses to identify priority research activities by Node, Technical Thrust Area, and material stream to maintain alignment of the research portfolio with each of the REMADE Institute's TPMs and its Strategic Investment Plan; and
- Gather additional impact information to prioritize those activities which yield the greatest impact consistent with the REMADE Institute's goals and mission and the priorities of REMADE's Members.

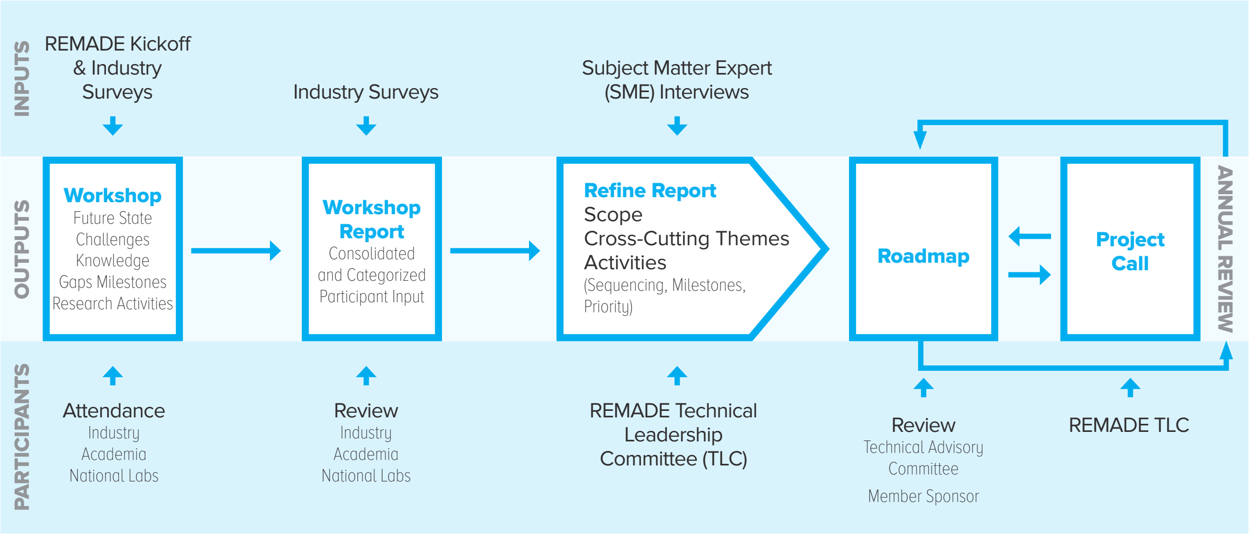
Annual updates will also be critical to ensure that the REMADE Technology Roadmap evolves with the changing landscape of U.S. manufacturing, including the advancement of existing manufacturing technologies and processes, the availability of emerging technologies, and shifting and emerging manufacturing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

Appendix A

Development of the Original (2018) 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 Roadmapping 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 2017 technology roadmapping process, workshop participants, the TLC, and the Department of Energy's Advanced Manufacturing Office (AMO) reviewed the workshop report and intermediate Technology Roadmap drafts prepared by the TLC and Nexight Group to further refine the content. Figure 6 summarizes the entire process.

Figure 6: Roadmap Development Process for the Original (2018) REMADE Technology Roadmap



Activities Prior to the Technology Roadmapping 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 Node to review the barriers from the August 2016 workshop and identify additional technical barriers.

Online Surveys

Based on the inputs from the REMADE Institute Kick-off Meeting, the TLC developed four online surveys aligned to the four stages of the material life cycle: 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 due to the limited time between the dates of the surveys' release and the workshop.

▶ Technology Roadmapping Workshop

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 Group 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 Technology 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 the REMADE Institute to achieve its TPMs and deliver impact to U.S. manufacturers. To maximize potential benefit to manufacturers, 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 Technology Roadmap which was reviewed by the TLC and key DOE-AMO staff. Based on input from AMO and subsequent edits by the TLC, additional versions of the Technology Roadmap were developed and iterated on with the AMO team and the TLC, leading to a draft public version of the Technology 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 public draft of REMADE's Technology Roadmap was published for comments.

▶ Development of the First and Second Project Call

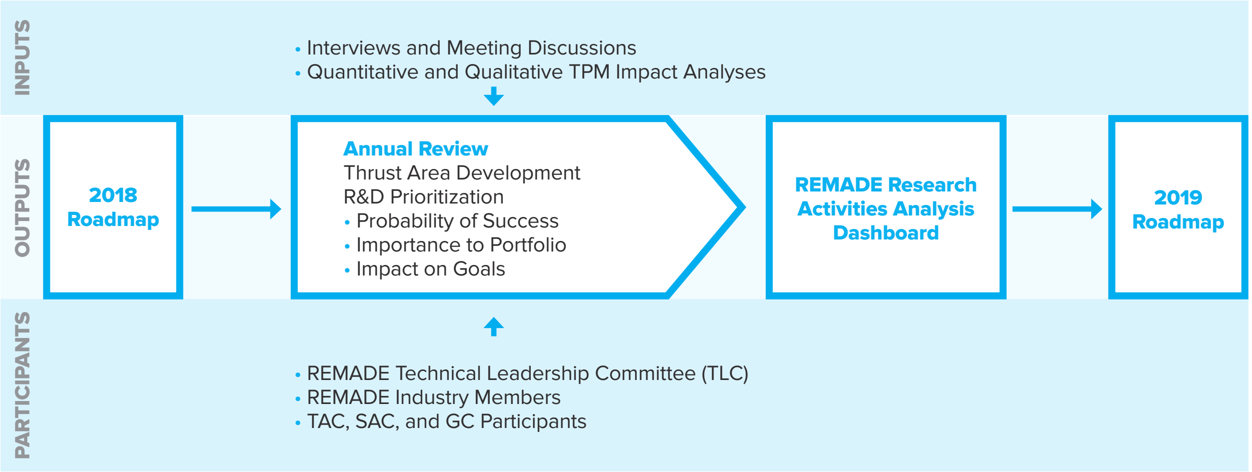
In parallel with the development of the Technology Roadmap, topics for the first and second project call were identified and prioritized using the process outlined in Figure 1 in the About This Document section of the Technology Roadmap.

Appendix B

2019 Technology Roadmap Update

The 2019 Roadmap was updated using the process summarized in figure 7, including 1) structured interviews with a number of REMADE industry Members who may have not have had an opportunity to contribute to the original Roadmap, 2) rigorous quantitative and qualitative analyses to identify R&D topics that would deliver the greatest impact relative to the REMADE Technical Performance Metrics (TPMs), 3) Technical Leadership Committee (TLC) assessment of the Probability of Success and Importance to REMADE's Research Portfolio associated with the various R&D topics, 4) informal discussions with REMADE Members at the Annual Meeting and through other venues to validate the results of the analyses, and 5) feedback provided by REMADE's Technical Advisory Committee (TAC), Strategic Advisory Committee (SAC), and Governance Committee (GC).

Figure 7: 2020 Roadmap Revision Process



To improve readability of the Technology Roadmap and accelerate the development and release of Requests for Proposals (RFPs), the TLC added start and end dates to the research activities, consolidated them into 14 Technical Thrusts Areas that were identified with assistance from the TAC, and organized each Thrust Area as a sequence of research activities displayed as a Gantt chart. These changes were also made to help Members develop proposal concepts and form teams in anticipation of upcoming project calls.

The REMADE Institute and Nexight also created an Analysis Dashboard and modified the layout of the Roadmap. Using the *Impact versus the TPMs*, *Importance to REMADE's Research Portfolio*, and *Probability of Success* ratings that the TLC had assigned to each research activity, Nexight created an interactive dashboard that allows the REMADE Institute to map each research activity on a graph showing *Impact/Importance* versus *Probability of Success*. The Dashboard also allows users to filter the R&D portfolio by Node, Technical Thrust Area, material class, and priority. As it updates the Strategic Investment Plan (SIP) each year and identifies RFP topics for future project calls, the REMADE Institute may use the Dashboard to validate that it is pursuing R&D activities that will deliver the highest impact versus the TPMs and are of greatest urgency in creating a more circular economy for metals, polymers, fibers, and e-waste.

The education and workforce development (EWD) activities originally found in the 2018 Technology Roadmap have been removed from this document and consolidated into a stand-alone EWD Roadmap that describes the REMADE Institute's three-tiered structure for organizing and delivering training products: Overview and Awareness Training, Short Course Modules, and REMADE Professional Certificates. The EWD Roadmap also identifies course content the REMADE Institute will develop.

Appendix C

Technology Roadmap Contributors

All contributors listed below attended the initial (2017) technology roadmapping workshop except for those indicated by an asterisk (*), who contributed via interviews following the workshop or Technology Roadmap reviews.

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Patrick White	Nexight Group
Bob Winskowicz	Sterilis
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Julie Zaniewski	Unilever
Hong-Chao Zhang	Texas Tech University
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Appendix D

Technical Performance Metrics

The U.S. Department of Energy developed the initial REMADE Institute concept and designed it to participate in the interagency National Network for Manufacturing Innovation (NNMI) program. The NNMI-defined overall objectives for each institute are:

- to research, develop and demonstrate high-impact new advanced manufacturing technologies that are adopted into the market at scale for energy efficient manufacturing and clean energy and energy efficient product manufacturing;
- to be financially self-sustaining after 5 years;
- to train an advanced manufacturing workforce;
- to enrich the innovation ecosystem;
- to strengthen U.S. manufacturing competitiveness; and
- to establish an industrial consortium as a public-private partnership (including small and medium sized manufacturers).

As part of the original charter for the REMADE Institute, the U.S. Department of Energy also developed the following qualitative and quantitative performance metrics. These metrics support the mission of the REMADE Institute and help measure progress towards the institute goals and the overall goals of the Manufacturing USA Institutes.

- **25% Improvement in Embodied Energy Efficiency**
  Demonstrate through innovative material reuse, recycling, remanufacturing and reprocessing technologies, a 25 percent (25%) improvement in embodied-energy efficiency (% change in BTU/ kg product) through first-of-their-kind demonstrations at manufacturing plants or major processes within five years of Institute operation, supporting a goal of at least fifty percent (50%) improvement in embodied-energy efficiency within ten years following initial Federal support for the REMADE Institute.

- **Demonstrate Potential for Cost Parity for Secondary Feedstocks and Energy Parity for Secondary Feedstocks**
  Develop tools and technologies to quantitatively increase energy productivity by reducing the cost of key secondary feedstocks in existing processes to at or below cost parity of primary feedstocks (modeled costs based on technologies being demonstrated) relative to the existing state-of-the-art within five years, and be on a pathway to achieve, at minimum, installed and operating cost parity for the secondary feedstocks at full scale.

- **Demonstrate 30% Increase in Recycling/Reuse Rate**
  Research, develop and demonstrate improved recycling and reuse in materials manufacturing to enable a 30% absolute increase in recycling rates of specific energy-intensive materials as a prioritized portfolio of technologies.

- **Demonstrate 20% Reduction in associated GHG Emissions and a 10X Reduction in Primary Feedstock Use**
  Improved Material Efficiency and Decreased GHG Emissions: Research, develop and demonstrate at representative pilot scale, at least one cost effective energy intensive/dependent process that achieves a 10x reduction in primary material feedstock (kg/kg product), with improved energy efficiency (% relative to baseline), and 20% lower GHG emissions (ton CO2 eq./kg) relative to commercial state-of-the art at the relevant production rate (kg per day).

- **Demonstrate 30% Secondary Feedstock Increase and 30% Primary Feedstock Reduction**
  Demonstrate approaches to cost-effective cross-industry use of secondary feedstocks. Develop and demonstrate at minimum pilot scale at least one process with relevant and quantified operating times that enables reuse of recycled and recovered materials to serve as cost effective material feedstocks for one or more different industries.

- **Demonstrate 30% Reduction in Energy to Process Secondary Feedstocks**
  Develop tools and technologies to reduce the total energy required to process secondary materials by thirty percent (30%) relative to the existing state-of-the-art within five years and be on a pathway to achieve a 50% reduction for the secondary materials processing at full scale within 10 years.

Appendix E

Research Portfolio Impact Analysis and Prioritization Methodology

To help readers better understand the content of the five Node chapters, this section describes the methodology that was used to conduct the analysis and validate whether the "high-priority" research activities identified in the Roadmap had been appropriately categorized.

In the 2018 Technology Roadmap, a subset of research activities for each Node was designated as "high-priority". A combination of factors was used to make this determination, including the following: participant voting conducted during the Technology Roadmap workshop, expert interviews, and importance to follow-on activities within the REMADE Institute research portfolio. For Systems Analysis & Integration and Design for Re-X research activities, much of this analysis was qualitative in nature.

In the process of updating the 2019 Technology Roadmap and the Strategic Investment Plan (SIP), REMADE sough to identify the "areas of greatest opportunity" to meet the TPMs for each material class and Node. The results of that analysis can be found in REMADE's 2019 *Strategic Investment Plan*.

In parallel, the TLC modified the lay-out of the research activities. Start and end dates were added to the research activities. This allowed the REMADE Institute to present the Technology Roadmap in the form of a Gantt Chart.

The research activities were also consolidated into 13 Technical Thrust Areas.

To provide the REMADE Institute a convenient mechanism for viewing its entire research portfolio and strategically allocating resources, REMADE and the Nexight Group evaluated each research activity based on three criteria:

▶ Impact versus the TPMs

The extent to which an activity will contribute to REMADE's goals

- Determined based solely on a) quantified mid-term (first five years of the REMADE Institute) energy, emission, and feedstock consumption impact that the REMADE Institute calculated during its analysis of areas of greatest opportunity to meet the TPMs conducted as part of the 2019 Technology Roadmap update; and (b) impacts that were calculated for projects recommended from the first, second, and third project calls.

Impact versus the TPMs Rating Criteria for Energy Savings (ES)		
LOW	**MEDIUM**	**HIGH**
< 5 PJ	5 PJ - 25 PJ	> 25 PJ

▶ Importance to REMADE's Research Portfolio

The extent to which an activity is foundational to future work

- Determined based on whether a research activity is key enabler for other research activities (it must be accomplished first) OR is important to do despite the lack of easily quantified impact versus the TPMs, which would be the case for most of the Systems Analysis and Design for Re-X research activities.

▶ Probability of Success

An estimate of the relative difficulty of an activity relative to other activities

- Determined using the additional criteria that the research activity could be accomplished in the first five years of the Institute to better bound the criteria for evaluating Probability of Success.

The same methodology was used to evaluate the research activities that have been added to the 2020 Technology Roadmap.

Appendix F

Industry Member Interviews

To determine whether the 2019 Technology Roadmap represented the needs of its Members, and to identify priorities that should be incorporated into the Technology Roadmap, the REMADE Institute held a series of interviews with its industry partners during the summer and fall of 2019. The interviews not only informed the Technology Roadmap update, but they also helped REMADE identify research opportunities that were subsequently incorporated into the analysis of areas of greatest opportunity to meet the TPMs.

To initiate the process, all industry Members were invited to participate in the interviews, which were intended to help the REMADE Institute better understand its Members' expectations, their motivation for joining REMADE, and whether they had specific research recommendations that had not been adequately covered in the initial Technology Roadmap. To collect this feedback, the REMADE Institute developed a series of questions that were provided to all interviewees in advance of the meeting.

1. What benefits is your organization hoping to derive through its participation in REMADE?
2. How will your company measure the value of your participation in REMADE?
3. What megatrends or externalities might shift the recycling and remanufacturing landscape? Is your company actively planning for such potential future scenarios?
4. Are there specific REMADE-relevant technical challenges that your company is dealing with that you would like to see the REMADE Institute address?
5. Are there specific REMADE-relevant economic challenges that your company is dealing with that you would like to see the REMADE Institute address? Do you believe these challenges are broadly impacting your industry, or are they specific to your organization?
6. Have you looked at the REMADE Technology Roadmap that was released earlier this year? If so, does it capture the technical and economic challenges you provided?
7. Can you identify one topic from the list above that you would like to see included in an upcoming project call? Is the topic of enough interest that your organization would be willing to invest cost-share to address this topic?

Twelve organizations representing the perspectives of the plastics industry, paper industry, remanufacturing industry, and metals and e-waste recycling industries participated in the interviews. All the organizations indicated that the REMADE Technology Roadmap was comprehensive and covered research opportunities that were of key interest to their respective organizations. Specific topics grouped into themes which were identified and subsequently incorporated into the TPM analysis and the Technology Roadmap are listed below. The numbers associated with each topic indicate the number of industry Members who identified a particular topic as important.

Technology

- Greater understanding of how and why the physical properties of virgin and recycled materials are different (3)
- Chemical vs Mechanical Recycling (2)
- Reduction of material losses and waste generated during reprocessing of recyclables (2)
- Carpet recycling, particularly for carpets made of PET
- More efficient mechanical sortation technologies
- Material loses and waste generation during reprocessing of recyclables
- De-manufacturing and recycling of solar panels
- Understanding macro-segregation in casting alloys
- Development of high-performance materials that can tolerate higher levels of secondary feedstocks

Techno-economics of Recycling

- Cost of recycling is an economic barrier (3)
- Technical and economic rationale for employing new technologies (3)
- Development of technologies capable of achieving cost and energy parity (2)
- Export markets refusing to accept domestic scrap materials and the impact of tariffs on scrap markets (2)
- Costs associated with collection, distribution, and processing of e-waste materials
- Material mapping

Policy/Standards

- Development of standards for recycled and remanufactured materials and products (5)
- Specifications for electronic shred materials
- Material optimization

Appendix G

Evaluation of Research Activity Impacts

As part of the 2019 Technology Roadmap update, REMADE sought to identify the “areas of greatest opportunity” for each material class and Node. The objectives of the analysis of the TPMs were to:

- quantify the baseline energy and material flows for each material class that would serve as a baseline for the REMADE Institute to use as it evaluated progress toward meeting the TPMs
- quantify the expected impact that each Node would contribute toward achieving the REMADE TPMs
- establish a framework for how best to allocate REMADE Institute funding to each Node to achieve the TPMs

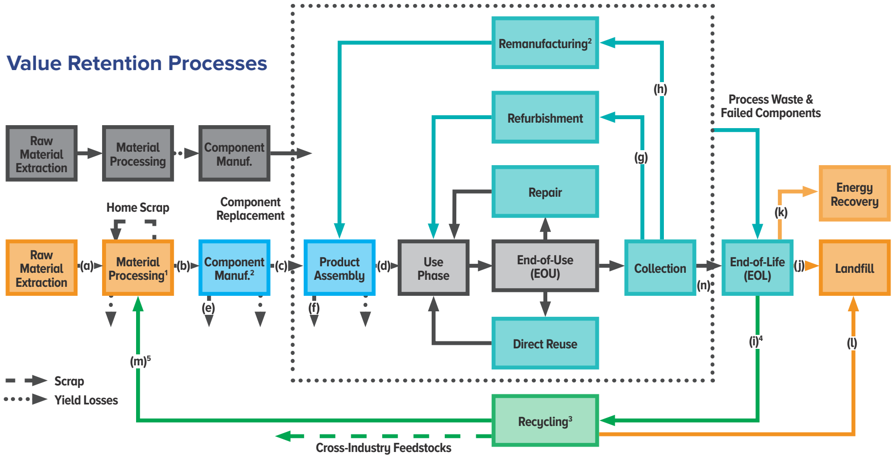
To that end, a materials flow and embodied energy analysis was conducted for each materials class. Using the various stages of the materials life cycle and the questions listed in Figure 8 as a framework, REMADE sought to identify specific opportunities to impact the TPMs that were relevant to each of the five Nodes and quantify the impact of those opportunities. The opportunities associated with remanufacturing were evaluated based on a manufacturing sectoral analysis and the current and projected remanufacturing intensity in each sector.

Opportunities that were identified and quantified came from two sources.

The first source was based on analyzing broad research themes as opposed to specific research projects. Examples of broad research themes include recovery of polymers and metals from e-waste and recovery of PET from textiles (clothing and carpet). Based on publicly available data for production and recycling volumes, as well as current recycling rates, the REMADE Institute quantified the embodied energy and energy consumption associated with processing these materials, and the resultant savings were calculated.

The second source of opportunities was the 31 projects from the first and second project calls that were recommended for negotiation. The nine projects selected from the third project call were added to the analysis in 2020. The impacts for each project are based on assumptions regarding the volume of material that would be impacted by the projects and assume that the technology has been fully adopted by U.S. manufacturing supply chains. As a result, it represents an upper bound for potential impact. Finally, opportunities that were identified through the industrial Member interviews were also included in the TPM opportunity analysis and subsequently integrated into the Technology Roadmap.

Figure 8: Framework Used to Evaluate the Areas of Greatest Opportunity and TPM Impacts



(a) primary material input
(b) intermediate products (alloys, semis, plastic resins, fibers)
(c) parts/components
(d) modules, sub-assemblies, products
(e) scrap produced at Manufacturing (new scrap)
(f) scrap produced during Product Assembly
(g) EOU products collected for refurbishment
(h) EOU products collected for remanufacturing
(i) End-of-Life (EOL) waste streams collected for recycling
(j) EOL waste streams to be landfilled
(k) EOL waste streams combusted for energy recovery
(l) Recycling waste streams to be landfilled
(m) Recycled materials used to create secondary feedstock
(n) EOL products

Questions to Address for Each Material Class

Production
- What are the current production and consumption volumes?
- What is the primary/secondary feedstock ratio?
- What production processes are used?
- Where do material losses occur at each step of production?

Recycling
- What are the collection pathways/ rates?
- What is the current recycling rate?
- Where do material losses occur at each step of recycling and why?

Analysis
- Where are the greatest opportunities?
- What impact will they have toward meeting the TPMs?

For each material class, the REMADE Institute has constructed tables that specify the maximum embodied energy and materials savings for each opportunity, the Node the opportunity is aligned with, and the estimated mid-term (5-year) impact that might be achieved because of REMADE Institute research investments. These calculations are reviewed following each RFP to track progress toward meeting the TPMs. They are also reviewed and (if necessary) updated at the end of each project based on the technology that was developed as part of the project.

Appendix H

Relevant References

Alliance for Pulp & Paper Technology Innovation (APPTI). Cellulose Nanometerials. Washington, D.C.: APPTI, 2016.

Alliance for Pulp & Paper Technology Innovation (APPTI). Next Generation Pulping Roadmap. Washington, D.C.: APPTI, 2016.

Alliance for Pulp & Paper Technology Innovation (APPTI). Reuse of Process Effluents Roadmap. Washington, D.C.: APPTI, 2016.

Alliance for Pulp & Paper Technology Innovation (APPTI). Technologies for Advanced Manufacturing of Pulp and Paper Products. Washington, D.C.: APPTI, 2016.

Allwood, Julian M. et al. “Material efficiency: A White Paper.” Resources, Conservation and Recycling. 55 (2011), 362–381.

Allwood, Julian M. and Jonathan M. Cullen. Sustainable Materials with Both Eyes Open. United Kingdom: UIT Cambridge Ltd., 2012.

American Chamber of Commerce to the European Union (AmCham EU). The Circular Economy: 10 Innovative Business Solutions and How to Go Further. Brussels, Belgium: AmCham EU, 2016.

American Chemistry Council (ACC), Plastics Division. Plastics and Polymer Composites Technology Roadmap for Automotive Markets. Washington, D.C.: ACC, 2014.

American Metalcasting Consortium. Metalcasting Industry Roadmap. Summerville, SC: May 2016.

Broadbent, Clare. “Steel’s recyclability: demonstrating the benefits of recycling steel to achieve a circular economy.” The International Journal of Life Cycle Assessment 21 (2016): 1658-1665.

Carmona, Luis Gabriel et al. “Material Services with Both Eyes Wide Open.” Sustainability 9 (2017): 1-23.

Center for Automotive Research (CAR). Technology Roadmaps: Intelligent Mobility Technology, Materials and Manufacturing Processes, and Light Duty Vehicle Propulsion. Ann Arbor: CAR, June 2017.

Chen, Wei-Qiang and T.E. Graedel. “Dynamic Analysis of Aluminum Stocks and Flows in the United States: 1900-2009.” Ecological Economics. 81 (2012): 92-102.

Clark, James H. et al. “Circular economy design considerations for research and process development in the chemical sciences.” Green Chemistry. 1463-9262 (2016): 3914-3934.

Confederation of European Paper Industries (CEPI). Unfold the Future: The Age of Fibre. Belgium: CEPI, 2015.

Confederation of European Paper Industries (CEPI). Unfold the Future: The Forest Fibre Industry. Belgium: CEPI, 2011.

Confederation of European Paper Industries (CEPI). Unfold the Future: The Two Team Project. Belgium: CEPI, 2013.

Deloitte Sustainability. Circular economy potential for climate change mitigation. United Kingdom: Deloitte, November 2016.

Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH, The Energy and Resources Institute (TERI), Development Alternatives, VDI Zentrum Ressourceneffizienz (VDI-ZRE), and Institut für Energieund Umweltforschung Heidelberg (IFEU). Strategy Paper on Resource Efficiency. India: National Institution for Transforming India (NITI Aayog), June 2017.

Ellen MacArthur Foundation. “Circular Economy Resources.” Webpage. 2017.

Ellen MacArthur Foundation. Towards the Circular Economy: Economic and Business Rationale for an Accelerated Transition. Cowes, United Kingdom: Ellen MacArthur Foundation, 2013.

European Academies Science Advisory Council (EASAC). Priorities for critical materials for a circular economy. Germany: German National Academy of Sciences, 2016.

European Environment Agency (EEA). More from Less—Material Resources Efficiency in Europe: 2015 overview of policies, instruments, and targets in 32 countries, Country profile: Netherlands. Copenhagen K, Denmark: EEA, 2015.

European Remanufacturing Network. Remanufacturing Market Study. United Kingdom: European Remanufacturing Network, 2015.

European Union (EU). Roadmap Document for a Sustainable Chemical Industry. Brussels, Belgium: EU, 2013.

European Union (EU). Strategic Implementation Plan for European Innovation Partnership on Raw Materials, Part I. Brussels, Belgium: EU, 2013.

European Union (EU). Strategic Implementation Plan for European Innovation Partnership on Raw Materials, Part II: Priority Areas, Action Areas, and Actions. Brussels, Belgium: EU, 2013.

European Union (EU). Strategy on Plastics in a Circular Economy. Brussels, Belgium: EU, 2017.

Florin, N., E. Dominish, and D. Giurco. Action Agenda for Resource Productivity and Innovation: Opportunities for Australia in the Circular Economy. Sydney: Institute for Sustainable Futures – University of Technology Sydney, 2015.

Forging Industry Education and Research Foundation (FIERF). Forging Industry Technology Roadmap 2016 Revision. Cleveland: FIERF, April 2016.

Geyer, Roland, Jenna R. Jambeck, Kara Lavender Law. “Production, use, and fate of all plastics ever made.” Science Advances 3 (2017): 1-5.

Ghisellini, Patriza, Catia Cialani, and Sergio Ulgiati. “A review on circular economy: the expected transition to a balanced interplay of environmental and economic systems.” Journal of Cleaner Production 114 (2015): 11-32.

Institute for Advanced Composites Manufacturing Innovation (IACMI). Technology Roadmap. Knoxville, TN: IACMI, 2017.

International Aluminum Institute (IAI). Alumina Technology Roadmap. United Kingdom: IAI, 2011.

International Council of Forest & Paper Associations (ICFPA). 2015 ICFPA Sustainability Progress Report. ICFPA, 2015.

International Electronics Manufacturing Initiative (iNEMI). 2015 Research Priorities. Herndon, VA: iNEMI, 2015.

International Electronics Manufacturing Initiative (iNEMI). 2017 Roadmap. Herndon, VA: iNEMI, 2017.

International Resource Panel and European Commission. Workshop Report: Promoting Remanufacturing, Refurbishment, Repair, and Direct Reuse, as a contribution to the G7 Alliance on Resource Efficiency, 7-8 February 2017Brussels, Belgium. Brussels, Belgium: European Union (EU), 2017.

Lightweight Innovations for Tomorrow (LIFT). Pillar Roadmap: Joining and Assembly, Coatings, Powder Processing, Melt Processing etc. Michigan: LIFT, 2016.

Liss, Gary, et al. A Guide to Sustainable Materials Management and Summary of White Paper Ideas. Syracuse, NY: National Recycling Coalition, May 2015.

Malaysia Automotive Institute (MAI). The Six Automotive Roadmaps. Malaysia: MAI, 2017.

Mars, Carole, Jennifer Mangold, and Margot Hutchins. Definition of an Ideal Used Electronics Management Program. Arizona: The Sustainability Consortium, July 2014.

Mars, Carole, Christopher Nafe, and Jason Linnell. The Electronics Recycling Landscape Report. Arizona: The Sustainability Consortium, May 2016.

Metal Powder Industries Federation (MPIF). 2017 PM Industry Roadmap: Technology Update for the Powder Metallurgy Industry. Princeton, NJ: MPIF, 2017.

Miller, Theresa, Caroline Kramer, and Aaron Fisher. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Pulp and Paper Manufacturing. Washington, D.C.: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, Advanced Manufacturing Office, June 2015.

Partnership for Research and Innovation in Sustainable Manufacturing (PRISM). PRISM Workshop on Sustainable Manufacturing for the Aerospace Industry: Product, Process and System Innovations for Next Generation Manufacturing: Pre-read Material. Lexington, KY: University of Kentucky – Institute for Sustainable Manufacturing (UK-ISM), 2015.

Pauliuk, Stefan, Tao Wang, and Daniel B. Müller. “Steel all Over the World: Estimating In-Use Stocks of Iron for 200 Countries.” Resources, Conservation and Recycling. 71 (2013): 22-30.

Pauliuk, Stefan, et al. “The Steel Scrap Age.” Journal of Environmental Science & Technology. 47 (2013): 3448-3454.

Plastics Europe. Towards a Life Cycle Driven Circular Economy. Brussels, Belgium: Plastics Europe, 2015.

RAMP-UP. State-of-the-art for Additive Manufacturing of Metals: Roadmap for research and innovation to industrialize additive manufacturing of metals in Sweden.

Rizos, Vasileios et al. The Circular Economy: Barriers and Opportunities for SMEs, Working Document No. 412. Brussels, Belgium: Centre for European Policy Studies, September 2015.

Rochester Institute of Technology (RIT) Center of Excellence in Advanced Manufacturing. “Designing the Circular Economy: Lessons from MIT.” Blog. May 22, 2017.

Rochester Institute of Technology (RIT) Golisano Institute for Sustainability. Technology Roadmap for Remanufacturing in the Circular Economy. Rochester, NY: RIT Golisano Institute for Sustainability, May 2017.

Sames, W.J. et al. “The metallurgy and processing science of metal additive manufacturing.” International Materials Reviews, DOI 10.1080/09506608.2015.1116649. 2016: 1-46.

Sander, Knut et al. Recycling Potential of Strategic Metals (ReStra). German: Federal Environment Agency, August 2017.

Skrzypinski, Catherine. “Market Report: How Carbon is Sharing Energy for Mines.” Energy and Mines. 2017.

Steel Market Development Institute. 2016 Steel Industry Technology Roadmap for Automotive. Southfield, MI: Steel Market Development Institute, August 2016.

Tsuji, Karl and Mihir Torsekar. Aluminum: Competitive Conditions Affecting the U.S. Industry. Washington, D.C.: United States International Trade Commission, June 2017. Publication Number: 4703. Investigation Number: 332-557.

U.S. Business Council for Sustainable Development (US BCSD), the Corporate Eco Forum (CEF), and the World Business Council for Sustainable Development (WBCSD). United States Materials Marketplace Pilot Project Report. Austin, TX: US, BCSD, CEF, WBCSD, 2015.

U.S. Department of Energy (DOE). Flow of Materials through Industry/Sustainable Manufacturing Technology Assessment. Washington, D.C.: DOE, 2015.

U.S. Department of Energy (DOE), Institute of Paper Science & Technology (IPST) at Georgia Institute of Technology, and American Forest & Paper Association (AF&PA), prepared by the Alliance for Pulp & Paper Technology Innovation (APPTI). Forest Products Industry Technology Roadmap. Washington, D.C.: APPTI, April 2010.

U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), prepared by Energetics Incorporated. Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in U.S. Chemical Manufacturing. Washington, D.C.: Advanced Manufacturing Office (AMO), DOE EERE, June 2015.

U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), prepared by Energetics Incorporated. DRAFT—Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Advanced High Strength Steel. Washington, D.C.: National Renewable Energy Laboratory (NREL), DOE EERE, March 2016.

U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), prepared by Energetics Incorporated. DRAFT—Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Aluminum. Washington, D.C.: National Renewable Energy Laboratory (NREL), DOE EERE, March 2016.

U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), prepared by Energetics Incorporated. DRAFT—Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Carbon Fiber Reinforced Polymer Composites. Washington, D.C.: National Renewable Energy Laboratory (NREL), DOE EERE, March 2016.

U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), prepared by Energetics Incorporated. DRAFT—Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Glass Fiber Reinforced Polymer Composites. Washington, D.C.: National Renewable Energy Laboratory (NREL), DOE EERE, March 2016.

U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), prepared by Energetics Incorporated. DRAFT—Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Magnesium. Washington, D.C.: National Renewable Energy Laboratory (NREL), DOE EERE, March 2016.

U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), prepared by Energetics Incorporated. DRAFT—Bandwidth Study on Energy Use and Potential Energy Saving Opportunities in the Manufacturing of Lightweight Materials: Titanium. Washington, D.C.: National Renewable Energy Laboratory (NREL), DOE EERE, March 2016.

U.S. Department of Energy (DOE), Industrial Technologies Program (OIT), prepared by Energetics Incorporated. Energy and Environmental Profile of the U.S. Petroleum Refining Industry. Washington, D.C.: U.S. Department of Energy, Industrial Technologies Program, November 2007.

U.S. Department of Energy (DOE), Office of Industrial Technologies (OIT), prepared by Energetics Incorporated. Energy and Environmental Profile of the U.S. Chemical Industry. Washington, D.C.: DOE OIT, May 2000.

U.S. Department of Energy (DOE), Office of Energy Efficiency & Renewable Energy (EERE), U.S. Drive Partnership. Materials Technical Team Roadmap. Washington, D.C.: DOE, October 2017.

U.S. Environmental Protection Agency (EPA). “Sustainable Electronics Roadmap.” PowerPoint. Washington, D.C.: EPA, 2012.

U.S. Environmental Protection Agency (EPA). U.S. EPA Sustainable Materials Management Program Strategic Plan: Fiscal Year 2017-2022. Washington, D.C.: EPA, 2015.

U.S. Environmental Protection Encouragement Agency (EPEA). “Cradle to Cradle: Innovation, quality and good design.” Webpage. 2017.

Van Ewijk, Stijn, Julia A. Stegemann, and Paul Ekins. “Global Life Cycle Paper Flows, Recycling Metrics, and Material Efficiency.” Journal of Industrial Ecology (2017): 1-8.

World Business Council for Sustainable Development (WBCSD), Forest Solutions Group. Facts & Trends: Fresh & Recycled Fiber Complementarity. New York: WBCSD, 2015.

World Economic Forum (WEF). The New Plastics Economy: Rethinking the Future of Plastics. Geneva, Switzerland: WEF, 2016.

World Steel Association. Steel – The Permanent Material in the Circular Economy. Brussels, Belgium: World Steel Association, 2016.