REMADE Institute Technology Roadmap 2023

January 2023

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About This Document

The 2022 REMADE Institute Technology Roadmap represents the fourth iteration of this roadmap. To develop the initial roadmap released in 2018, the REMADE Institute partnered with Nexight Group, a technical and management consultancy specializing in technology roadmapping. To solicit industry feedback required to accurately define its research priorities, the REMADE Institute held a technology roadmapping workshop in September 2017. Augmented by interviews and online surveys, this workshop brought together subject matter experts (SMEs) from industry, academia, 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 2019, 2020, and 2022 Technology Roadmap updates. Figure 1 identifies the inputs (information) the REMADE Institute collected and the scope of changes it introduced when the roadmap was first developed and in subsequent roadmap updates.

Although Figure 1 portrays each technology roadmap update as a sequence of events, updating the technology roadmap is typically the last step in an annual (or, at a minimum, budget period) cycle of technology development-related activities. Figure 2 illustrates this cycle in greater detail. First, the Technical Leadership Committee (TLC) uses the information it collected while updating the technology roadmap to write and release a Request for Proposals (RFP) (step 1). Then, aided by merit review panels, the TLC selects projects to recommend to the Governance Board (GB) and the U.S. Department of Energy (DOE). After projects have been selected (step 2), the project managers and the Chief Technology Officer (CTO) estimate the Technical Performance Metric (TPM) impact of each project and update the TPM impacts of the entire portfolio (step 3). Appendix A contains a list of the TPMs the DOE initially established for the REMADE Institute. Next, Appendix B outlines the REMADE Institute's process to calculate the TPM impacts of its project portfolio. Finally, Appendix C explains the methodology for establishing research activities' impact, importance, and prioritization. Once the REMADE Institute launches these projects (step 4), the CTO, TLC, and project managers begin to update the technology roadmap. First, the CTO, TLC, and project managers identify gaps in the technology portfolio (step 5). These gaps may refer to research activities or material classes in the technology roadmap the current portfolio still needs to address or TPM impacts the portfolio still needs to meet. In addition to identifying gaps in the technology portfolio, the TLC also collects feedback from REMADE Institute Members (step 6) to better understand their priorities. Then, using the information gathered in steps 3-6, the CTO, the TLC, and the project managers update the technology roadmap again.

Appendix D provides a detailed discussion of the 2018 Technology Roadmap development process and describes the information (steps 3-6) the REMADE Institute gathered as it updated the technology roadmap in 2019, 2020, and 2022. Appendix E identifies the technology roadmap contributors. Appendix F describes the organization of the Request for Information (RFI) the REMADE Institute released in January 2022, discusses the key findings provided by RFI respondents, and summarizes the feedback collected during industry interviews the REMADE Institute conducted to clarify RFI feedback received. Finally, Appendix G explains how the REMADE Institute used the information gathered from the RFI responses and Member interviews to update this Technology Roadmap.

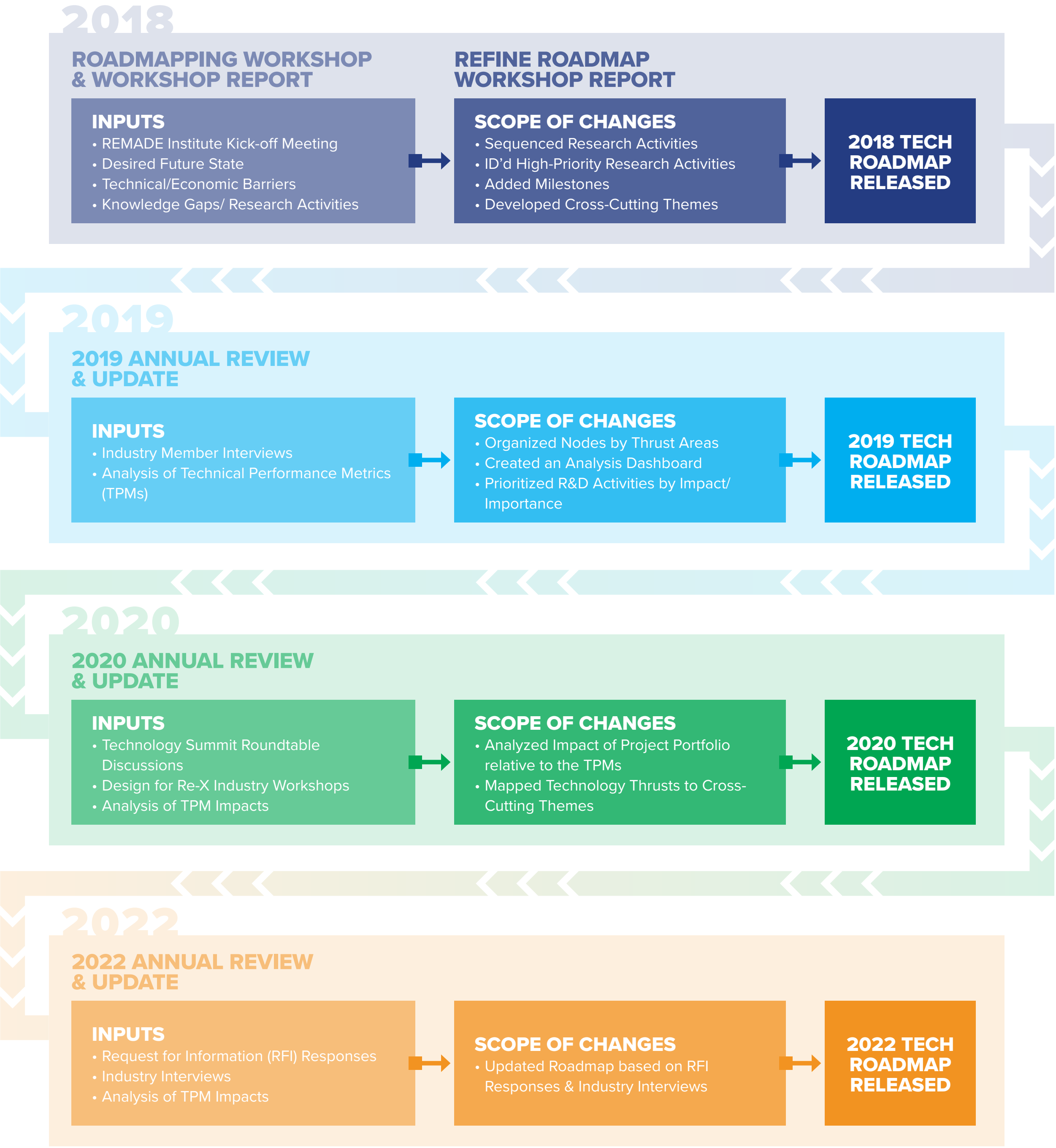

Figure 1: Technology Roadmap Development Process

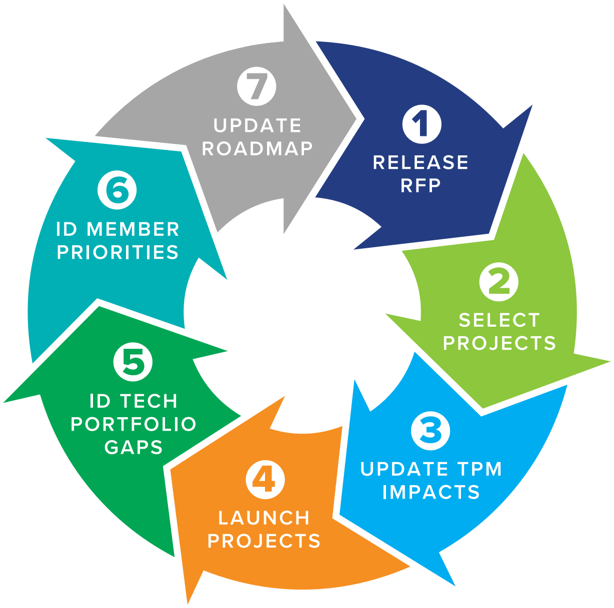

Figure 2: The Cycle of REMADE Institute Technology Development-Related Activities

2022 Technology Roadmap Update

The TLC and project managers updated the 2022 Technology Roadmap based on information collected while performing steps 3-6 in Figure 2. The data generated or collected after the selection of projects from RFP 5 (step 2) included the following: updated TPM impact estimates, gaps identified in the technology portfolio, responses they received to their January 2022 RFI, and one-on-one interviews conducted with REMADE Institute Members. In addition, the GB, Strategic Advisory Committee (SAC), and Technical Advisory Committee (TAC) provided feedback and guidance throughout the process.

Summary of the Key Changes Made in the 2022 Technology Roadmap Update

As discussed earlier, Appendix F details how the REMADE Institute solicited input and summarizes respondents' feedback. Appendix G discusses how the REMADE Institute used that information to update this technology roadmap, details the changes made in the 2022 Technology Roadmap update, and explains the rationale behind these changes. This Appendix also describes how these changes will improve the REMADE Institute’s ability to achieve its goals and TPMs.

The revised and updated 2022 Technology Roadmap is divided into the following sections:

▶ Introduction

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

Node Chapters

This section contains a detailed discussion of the five REMADE Institute Nodes. Each chapter describes the focus of work performed within the Node, identifies the future state of the industry as envisioned by industry stakeholders, and outlines the technical and economic challenges relevant to that Node that industry currently faces[1]. In addition, each chapter presents a Gantt chart containing the research activities for each Technical Thrust Area required to reach the desired future state and achieve the REMADE Institute's mission. These research activities have been updated based on the feedback collected in response to the RFI and industry interviews.

The REMADE Institute has evaluated the TPM impacts for each research activity in the Gantt Chart to ensure that the REMADE Institute's research portfolio will deliver the most significant impact for its members and help the REMADE Institute achieve the TPMs. The three criteria used to measure impact are 1) Impact versus the TPMs, 2) Importance to the REMADE Institute's Research Portfolio, and 3) Probability of Success. Appendix C explains the research portfolio impact analysis and prioritization methodology.

High Priority REMADE Institute 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 the REMADE Institute should pursue over its five years of federal funding. These "high-priority" activities have been consolidated into this single section and organized by Technical Thrust Area.

Next Steps

Because the Technology Roadmap is a forward-looking document, it should be considered a living document that the Institute will regularly re-evaluate and revise to ensure it remains current and relevant. With input from industry stakeholders and support from its industry, academia, national laboratories, and trade associations, the REMADE Institute will revisit this Technology Roadmap periodically to ensure it evolves based on the following considerations:

- Progress or pacing of proposed activities
- Emergence of innovative technologies or advancements in 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:

- Appendix A: REMADE Institute Technical Performance Metrics (TPMs)
- Appendix B: Establishing the 5-year Technical Performance Metric (TPM) Goals and Analyzing the Impact of Research Activities & the Technology Portfolio
- Appendix C: Methodology to Establish the Impact, Importance, and Prioritization of Research Activities

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[1] For each node, the underlying knowledge gaps for each technical and economic challenge are provided in *Appendix D: Knowledge Gaps That Must be Overcome to Tackle the Technical and Economic Challenges for Each Node*

- Appendix D: Development of the 2018 REMADE Institute Technology Roadmap and Updates to the 2019 and 2020 Technology Roadmap
- Appendix E: Technology Roadmap Contributors
- Appendix F: Summary of 2022 RFI Responses and Industry Member Interviews
- Appendix G: Process the REMADE Institute Used to Translate RFI and Industry Interview Responses into 2022 Technology Roadmap Updates
- Appendix H: Knowledge Gaps the REMADE Institute Must Address to Overcome the Technical and Economic Challenges for Each Node
- Appendix I: Relevant References

List of Abbreviations

ABS	Acrylonitrile Butadiene Styrene
AI	Artificial Intelligence
AMO	Advanced Manufacturing Office
ASR	Automotive Shredder Residue
BTU	British Thermal Unit
CAD	Computer-Aided Design
CRT	Cathode-Ray Tube
CTO	Chief Technology Officer
DOE	U.S. Department of Energy
EOL	End-of-Life
EOU	End-of-Use
EU	European Union
EV	Electrical Vehicle
EVA	Ethyl-Vinyl Acetate
EWD	Education & Workforce Development
GB	Governance Board
GHG	Greenhouse Gas Emissions
HDPE	High-Density Polyethylene
ICEV	Internal Combustion Engine Vehicle
kg	Kilogram
LCA	Life Cycle Assessment
MFA	Material Flow Analysis
ML	Machine Learning
MMT	Million Metric Tons (Tonnes)
MMTCO$_2$E	Million Metric Tons (tonnes) of Carbon Dioxide Equivalent
MRF	Material Recovery Facility
MRFF	Materials Recovery for the Future
MSW	Municipal Solid Waste
MWPF	Mixed-Waste Processing Facilities
NDE	Non-destructive Evaluation
PC	Polycarbonate
PC-ABS	Polycarbonate/Acrylonitrile Butadiene Styrene
PCBs	Printed Circuit Board
PE	Polyethylene
PET	Polyethylene Terephthalate
PJ	Petajoules
PP	Polypropylene
PV	Photo-Voltaic
PS	Polystyrene
R&D	Research & Development
Re-X	Reuse, Remanufacturing, Recovery, & Recycling
RFI	Request for Information
RFP	Request for Proposals
SAC	Strategic Advisory Committee
SMEs	Subject-Matter Experts
TAC	Technical Advisory Committee
TLC	Technical Leadership Committee
TPM	Technical Performance Metrics
UV	Ultraviolet

Introduction

Background, Mission, & Goals

Today, manufacturing accounts for approximately 25 percent of U.S. energy consumption. However, with improvements in materials production and processing, the U.S. could significantly increase manufacturing energy efficiency and reduce embodied energy and emissions, yielding substantial economic savings. To help realize these opportunities, the REMADE Institute—a $140 million Manufacturing USA Institute co-funded by the DOE—was launched in January 2017.

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.

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, the REMADE Institute focuses on increasing the reuse, remanufacturing, recovery, and recycling (collectively referred to as Re-X) of metals, fibers, polymers, and electronic scrap (commonly referred to as e-scrap, e-waste, or used electronics and electrical products)[2].

Through its research and education and workforce development (EWD) activities, the REMADE Institute seeks to eliminate or mitigate the technical and economic barriers that prevent greater material Re-X. As a result, the REMADE Institute seeks to motivate the subsequent industry investments required to complete technology development and deploy these technologies across the U.S. manufacturing ecosystem.

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

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

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[2] Historically, the REMADE Institute has used e-waste when referring to electronic waste. Based on discussions with trade associations and industry subject-matter experts, the REMADE Institute has replaced the term e-waste with e-scrap throughout this document. The motivations for making this change are as follows: 1) use of the term e-waste denotes that end-of-life electronics have no residual value and should be landfilled. In reality, used electronics can often be refurbished or recycled. Such electronics are not e-waste, 2) whether something is "waste" is an environmental regulatory issue, 3) the European Union (EU) and the Basel Convention have placed many restrictions on end-of-life (EOL) electronic products. In this context, use of the term e-waste suggests that EOL electronic products are waste products. According to the Basel Convention, e-scrap must be treated as hazardous waste. Wherever the reader sees the term e-scrap, they should understand that it refers to what the REMADE Institute previously called e-waste.

To measure progress towards these goals and guide the research agenda, the REMADE Institute has established **Technical Performance Metrics (TPMs)**. Figure 3 maps the REMADE TPMs to the Institute Goals.

	↓ 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	✓	✓	✓	✓	✓	✓

Figure 3: REMADE Institute Goals and Technical Performance Metrics (TPMs)

Technical Focus Areas

The current state of materials manufacturing technologies, tools, methods, and processes challenge the U.S.' ability to achieve 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 use of lower embodied-energy secondary feedstocks. At product EOL, 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 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 & EOL 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.

▶ 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 TAC, the Thrust Areas have been chosen consistent with terminology 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 by Thrust Area provides two benefits to the REMADE Institute. First, the REMADE Institute can prioritize similar activities with greater granularity. For example, organizing all sorting activities under the Mechanical Recycling Technologies Thrust Area makes it easier to determine which research activities to fund based on timing and TPM impacts. Second, the Thrust Areas provide the REMADE Institute with 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 the design, collection, sorting, cleaning, and separation of complex material streams. Figure 4 provides a brief description of each Node and Technical Thrust Area.

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.

- **Systems Analysis Methods, Tools, and Data**
  System insights on material flows (from MFA) and their embodied energy and associated emissions (from LCAs) allow the REMADE Institute to assess the impacts and opportunities related to 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 materials reuse, remanufacturing, recovery, and recycling within and across different industries. Relevant activities include the development of modeling tools to identify and address inefficiencies in the recovery and processing of recyclables and evaluate the economic impact of newly developed technologies and changing demand patterns on the availability of secondary feedstocks.

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.

- **Design for Re-X Assessment Frameworks**
  Frameworks that address design issues unique to one stage of the materials life cycle, such as Design for Recycled Content, Design for Remanufacturability, or Design for Product Assembly/Disassembly. The REMADE Institute may also develop Design for Circularity frameworks to help engineers evaluate design issues affecting multiple materials' life cycle stages.
- **Design for Re-X Tools**
  Tools to evaluate the life cycle (energy, emissions, and materials feedstocks) and financial impacts of design decisions on EOL disposition or the tradeoffs between initial production costs and revenue streams at EOL. The goal of research activities in this Technical Thrust Area is to pilot Design for Re-X tools that integrate with computer-aided design (CAD) systems and relevant LCA databases.

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.

- **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 the REMADE Institute will pursue include adjusting processing approaches, incorporating sensing technologies that provide real-time automated control and monitoring, and developing ML/AI tools and techniques to guide process development or enable real-time process adjustments.

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

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.

- **Robust, Non-destructive Inspection/ Evaluation Techniques**
  Inspection and evaluation techniques that allow remanufacturers to assess the damage and characterize the condition of mechanical, electrical, and electromechanical 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 (PCBs), 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

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-scrap.

- **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 (MSW), automobile shredders, and other waste streams) during collection and recovery. Projects that study the logistics associated with collecting and pre-processing 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 AI 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 thermochemical 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 previously identified and subsequently updated as part of the 2020 Technology Roadmap Update. Research activities in italics were added to the 2020 Technology Roadmap using the process described at the beginning of this document.

The following five chapters of this roadmap focus on the five Nodes. Each chapter begins with a vision of the Node's future state as identified by industry. In addition, each chapter identifies the critical technical and economic challenges the REMADE Institute must overcome to achieve that vision, and presents a comprehensive list of research activities needed to realize that vision. The desired future state and key technical and economic challenges were identified during the initial REMADE Institute Technology Roadmapping Workshop in September 2017 and have been refined as part of the 2019, 2020, and 2022 Technology Roadmap updates[4]. The research activities, for each Technology Thrust Area, have evolved since the release of the 2018 Technology Roadmap based on changes to the project portfolio, progress versus the REMADE Institute TPMs, and changing Member priorities. They will guide the Institute's RFP process, enabling the REMADE Institute to achieve its TPMs.

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[3] A core is a previously sold, worn or non-functional product or part, intended for the remanufacturing process. During reverse logistics, a core is protected, handled and identified for remanufacturing to avoid damage and to preserve its value.

[4] Appendix H provides a list of knowledge gaps that must be overcome to tackle the technical and economic challenges for each node

	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-scrap & 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 Institute Impact Calculator • Calculate REMADE TPM 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.

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

Systems Analysis & Integration

The **Systems Analysis & Integration** Node identifies strategic opportunities to reduce the embodied energy and emissions associated with materials production and processing. It also 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

U.S. industry has indicated that to understand the life cycle and economic impacts of sustainable manufacturing technologies and the flow of materials throughout the U.S. economy, the desired future state for systems analysis and integration tools, methods, and data applicable to Re-X should exhibit the following characteristics:

- Consistent methodologies (standards and protocols) for evaluating the life cycle impact of EOL Re-X processes have been developed.
- LCA databases have been updated to incorporate key EOL processes and include validated/verified U.S. data and relevant EU data.
- Tools for evaluating U.S. manufacturing energy and emissions include EOL processes.
- Methods/tools for analyzing material flows through supply chains incorporate secondary feedstocks and scrap material import/export data in their assessments.
- LCA 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 & Economic Challenges

For companies to realize the desired future state of systems analysis and integration tools, methods, and data applicable to Re-X, the research community and industry must work to overcome the following technical and economic challenges:

- Energy and emissions data for different materials and processes are unavailable or incomplete.
- It is challenging to provide guidance and strategic focus for the REMADE Institute's research efforts because existing LCA and materials flow analysis (MFA) information frequently focuses on specific materials or processes and does not consider systems interactions.

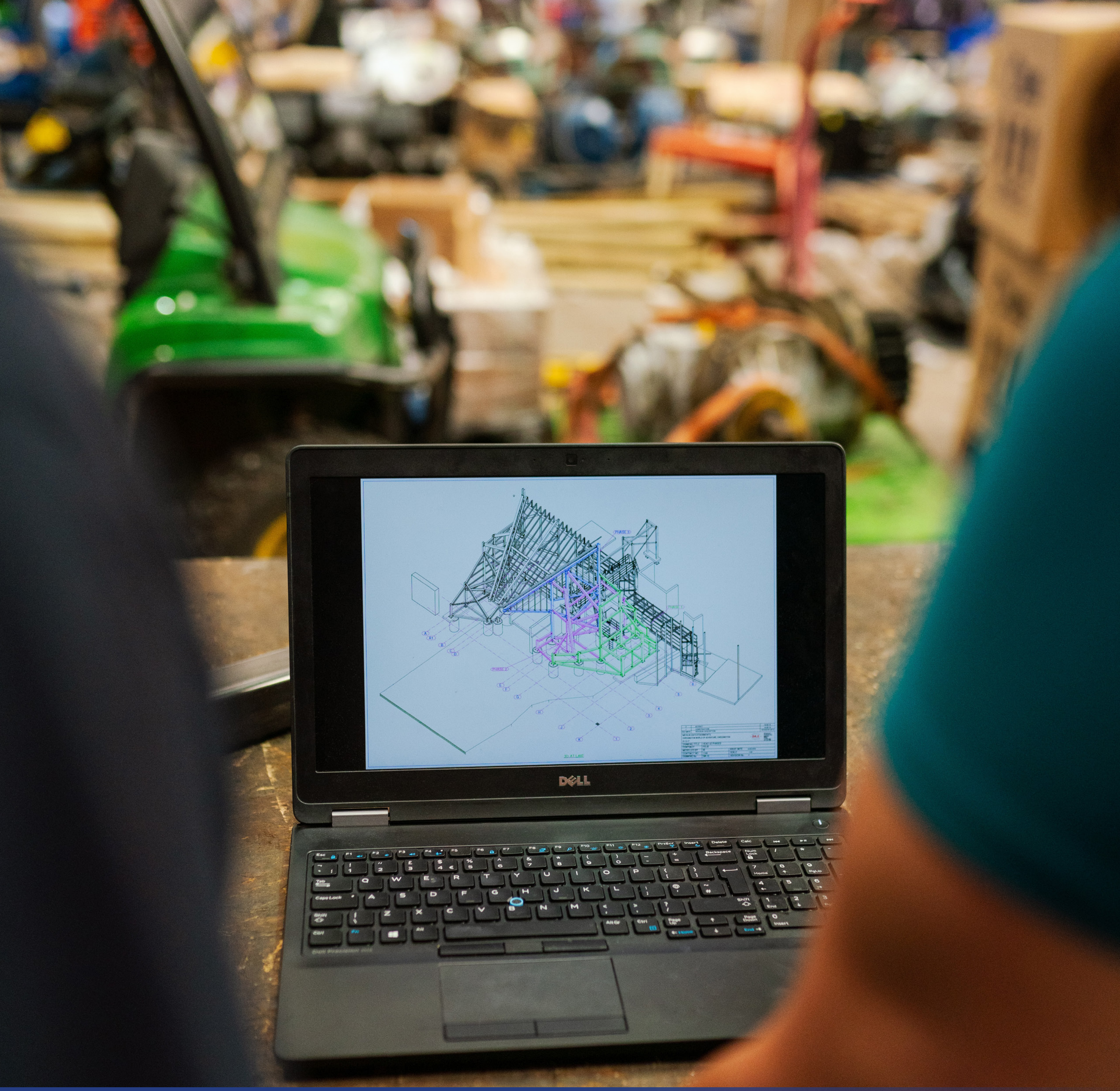
Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced systems analysis and integration tools, technologies, and techniques. Table 1 outlines **Systems Analysis & Integration** research priorities for the REMADE Institute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

Table 1: Systems Analysis & Integration 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			
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 two to five 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 Institute 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 cathode-ray tubes (CRTs), glass from material recovery facilities (MRFs), multilayers, paper vs flexible packaging waste)				█	█				✦✦✦	■■	✳
2	**Techno-economic Analysis Models and Tools**											
2.01	**Conduct a systems analysis case study for polyethylene terephthalate (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 the REMADE Institute 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 Institute TPMs				█					✦✦	■■	✳
2.07	Complete integrated assessment of multiple REMADE Institute 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			█	█	█	█			✦	■	✳✳



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

The **Design for Re-X** Node develops application domain-specific frameworks (such as Design for Remanufacturability). It also 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

U.S. industry has indicated that to facilitate better and more economical disassembly and increase material recovery at end-of-use (EOU) or EOL, the desired future state for design for Re-X tools and methods should exhibit the following characteristics:

- Established methodologies exist for assessing the extent to which a design enables Re-X at EOL.
- Standards exist and 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 EOL 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 & Economic Challenges

For companies to realize the desired future state of design for Re-X frameworks and tools, the research community and industry must work to overcome the following technical and economic challenges:

- Design specifications do not incorporate factors known to impact Re-X.
- Processes used to evaluate the benefits of Re-X do not encourage its adoption.
- Design engineers are not the ultimate decision-makers regarding the economic benefits of Re-X.
- Designers are hesitant to specify secondary feedstocks because material property data is frequently unavailable or incomplete. In addition, the extent to which material quality specifications should be adjusted to achieve equivalent performance is not well defined.
- Design and analysis methods and tools do not address the complexities required to adequately evaluate the design for Re-X trade-offs, assess risks, or address potential business implications.

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 the **Design for Re-X** research priorities for the REMADE Institute 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 lifecycle 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 (ML), deep learning, and generative algorithms to accelerate the 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

U.S. industry has indicated that to reduce energy and emissions during manufacturing and optimize primary and secondary material utilization, the desired future state for domestic manufacturing should exhibit the following 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 replace primary feedstocks.
- Improved or alternative manufacturing processes and technologies can make real-time adjustments to accommodate materials and chemistry variations or alternative feedstocks.
- Advanced simulation and optimization tools are available to guide process development for primary and secondary feedstocks used in manufacturing.
- Processes are available for cross-industry utilization of secondary feedstocks.

Technical & Economic Challenges

For companies to realize the desired future state of manufacturing materials optimization, the research community and industry must work to overcome the following technical and economic challenges:

- Secondary feedstock materials are less attractive to manufacturers because they exhibit greater compositional and material property variance.
- Production losses when manufacturers use secondary feedstocks in place of virgin material tend to be higher.
- Techniques for characterizing and evaluating material composition in real time are limited.
- Additional cost and complexity associated with using secondary feedstocks in manufacturing processes limit their use.
- Manufacturers do not effectively utilize material waste from current manufacturing processes to produce secondary feedstocks.
- 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.

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 **Manufacturing Materials Optimization** research priorities for the REMADE Institute 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 2018	2019	2020	2021	2022	2023	2024	2025	PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
5	**Characterization, Qualification, and Simulation Technologies**											
5.01	Develop cost-effective, rapid feedstock/material characterization techniques (e.g., in-situ spectral analysis technique) to enable real-time material quality measurements and composition adjustments of 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 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 reduce scrap generation (increase material efficiency) and directly 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 variations in secondary feedstock composition to reduce defects and scrap		█	█	█					✦	■■	✳✳
6.09	Develop machine learning (ML) and artificial intelligence (AI) tools and techniques that enable real-time process adjustments to accommodate the materials variations typically seen in secondary feedstocks and cross-industry feedstocks.				█	█	█	█		✦✦	■■	✳✳
6.10	**Develop ML/AI methods and tools to guide manufacturing process development when using secondary or cross-industry secondary feedstocks**					█	█	█		✦✦✦	■■	✳✳
6.11	Develop processing approaches to enable cross-industry uses of secondary feedstocks	█	█	█	█	█	█			✦✦✦	■	✳✳✳

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

US industry has indicated that to increase U.S. remanufacturing intensity[5], the desired future state for domestic remanufacturing and EOL reuse should exhibit the following characteristics:

- More cost-effective and 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.
- Remanufacturers have identified and pursued feasible opportunities for EOL reuse for a range of products not currently remanufactured or reused.
- Remanufacturers have developed more robust and cost-effective disassembly, cleaning, restoration, and condition assessment processes, improving material efficiency and cost parity of secondary materials in remanufacturing.
- Known, validated, and accepted industry standards for the 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 reduce total remanufacturing process energy have been identified.

Technical & Economic Challenges

For companies to realize the desired future state of remanufacturing and EOL reuse, the research community and industry must work to overcome the following technical and economic challenges:

- Lack of robust non-destructive inspection/evaluation techniques for assessing damage limits opportunities to remanufacture or reuse components.
- There are limited techniques for translating inspection or evaluation data into an assessment of residual value and the remaining life of products and components.
- Labor costs for key remanufacturing processes (such as component repair) limit reuse yield and remanufacturing intensity.
- Remanufacturers have not developed methods for restoring components to "like-new" condition, limiting component reuse in remanufacturing.
- Inefficiencies in the collection of EOL products limit cross-industry and cross-product reuse.

Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced remanufacturing and EOL reuse tools, technologies, and techniques. Table 4 outlines **Remanufacturing & End-of-life Reuse** research priorities for the REMADE Institute over the next 10 years, focusing initially on the first five.

[5] Total value of shipments of remanufactured goods as a share of total sales of all products within an industry sector.

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

●
●
● **High Priority Activity**

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

#	ACTIVITY DESCRIPTION	TIMELINE 2018	2019	2020	2021	2022	2023	2024	2025	PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
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	**Integrate sensor technologies and machine learning/artificial intelligence (ML/AI) methods to eliminate the need for destructive testing and enable rapid assessment of the quality of component repair/restoration processes.**			▬	▬					✦✦✦	■■■	✳✳
7.04	Integrate sensor technologies and ML/AI methods to rapidly characterize contaminants and assess cleanliness of parts prior to and following cleaning				▬	▬	▬			✦✦✦	■■	✳
7.05	Develop in situ methods or embedded sensors for tracking mechanical fatigue in products						▬	▬		✦✦✦	■■	✳
7.06	Develop methods to assess degradation in solid-state components									✦✦	■■	✳
7.07	Develop condition assessment methods for wind-turbine generators and drive trains and high-value EV cores and 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**			▬	▬	▬				✦✦	■■	✳✳
8.06	**Develop ML/AI tools and methods to automate non-destructive inspection/evaluation of cores (products returned for remanufacturing) and components (individual parts within the core)**			▬	▬	▬				✦✦	■■	✳✳✳
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 Institute 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**					▬	▬	▬		✦✦	■■■	✳✳✳
9.07	Develop processes to cost-effectively repair/restore wind-turbine generators and drive trains and high-value EV cores and components					▬	▬	▬		✦✦	■■	✳✳✳

Recycling & Recovery

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

Desired Future State of the Industry

U.S. industry has indicated that to increase domestic recycling rates and the availability of secondary feedstocks, the desired future state for domestic recycling and recovery should exhibit the following 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.
- MRFs can cost-effectively adapt to evolving changes in the content and volume of incoming waste streams.
- Material recyclers can respond to significant disruptions in market outlets for secondary materials and cost-effectively adapt to changing secondary material quality specifications/requirements.
- New markets with stable demand for secondary materials exist, significantly reducing landfilled waste.
- Improved supply chain logistics optimize the flow of scrap and recycled materials to minimize transportation, reduce costs, and meet customer demand for specific materials.

Technical & Economic Challenges

For companies to realize the desired future state of recycling and recovery, the research community and industry must work to overcome the following technical and economic challenges:

- The added cost of using secondary feedstock materials limits their attractiveness as a replacement for primary feedstocks.
- Existing reverse logistics networks for recycling and recovery are not well established for every REMADE Institute-relevant material, limiting the ability to collect and separate waste streams.
- Current cross-industry communication regarding the quality and availability of waste streams and secondary feedstocks limits recycling and recovery and increases costs.
- 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.
- 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.

Addressing these challenges will require coordinated efforts across the manufacturing community to develop, optimize, and implement advanced remanufacturing and EOL reuse tools, technologies, and techniques. Table 5 outlines **Recycling & Recovery** research priorities for the REMADE Institute 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 2018	2019	2020	2021	2022	2023	2024	2025	PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
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				🟩	🟩				✦✦	■■	✳✳
10.04	Improve collection and sorting of metals, polymers, fibers, and e-scrap to preserve their value and avoid downcycling.				🟩	🟩				✦✦	■■	✳✳
10.05	Apply machine learning/artificial intelligence (ML/AI) to improve identification, separation, and recovery of materials flowing through material recovery facilities (MRFs)				🟩	🟩				✦✦	■■■	✳✳✳
10.06	Develop reverse logistics tools to cost-effectively increase collection and recovery of end-of-life materials and products.				🟩	🟩				✦	■■	✳✳
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., Acrylonitrile butadiene styrene (ABS), Polystyrene (PS), Polycarbonate/Acrylonitrile butadiene styrene (PC-ABS), and Polycarbonate (PC) from e-scrap and automotive shredder residue (ASR)**			🟩	🟩	🟩				✦✦	■	✳✳✳
11.04	Develop cost-effective technology for separating small particle non-ferrous materials from e-scrap					🟩	🟩			✦✦	■	✳✳
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					🟩	🟩			✦	■■	✳✳
11.08	Develop technologies to cost-effectively separate metals, polymers, and glass in solar panels and electric vehicles.					🟩	🟩			✦✦	■■■	✳✳✳

● **High Priority Activity**

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

#	ACTIVITY DESCRIPTION	TIMELINE								PROBABILITY OF SUCCESS	PORTFOLIO IMPORTANCE	IMPACT
		2018	2019	2020	2021	2022	2023	2024	2025			
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 low-cost and energy-efficient chemical recycling technologies to improve the recycling rate of polymers (i.e., polyethylene terephthalate (PET), polyolefins) for non-textile/non-apparel applications					🟩	🟩	🟩		✦	■■	✳✳✳
12.05	**Develop low-cost and energy-efficient chemical recycling technologies to improve the recycling rate of polymers (i.e., PET, polyolefins) from textiles and apparel.**				🟩	🟩	🟩			✦	■■	✳✳✳
12.06	**Develop chemical or solvent-based approaches for removing pigments from polymers**					🟩	🟩	🟩		✦	■■■	✳✳✳
13	**Characterization, Cleaning, and Purification Technologies**											
13.01	**Develop cost-effective, and rapid 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					🟩	🟩	🟩		✦✦	■■■	✳✳✳
13.09	Develop ML/AI tools to characterize contaminants in recovered materials and identify the best-end use of materials based on contamination level.					🟩	🟩	🟩		✦✦	■■■	✳✳✳

High-Priority REMADE Institute Activities

High-Priority REMADE Institute Activities

A critical part of the REMADE Institute's coordinated strategy for achieving its goals is to identify and prioritize research activities necessary to address the most critical technical and economic 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 most significant impact on 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 following sources: 1) the 2017 Technology Roadmap workshop, 2) 2019, 2020, and 2022 Technology Roadmap updates, 3) industry Member interviews, 4) quantitative analysis of research activity impacts relative to the REMADE Institute's goals and TPMs, or 5) their importance to follow-on activities within the REMADE Institute's research portfolio. The high-priority activities for each Node are listed below.

Successfully developing innovative technologies or improving existing technologies or processes within the REMADE Institute's high-priority activity areas will facilitate measurable progress toward fulfilling the REMADE Institute's goals. In addition, to remain competitive in an increasingly global ecosystem, U.S. manufacturers must continue to embrace technologies and strategies that increase the adoption of Re-X. Through its targeted and collaborative approach, the REMADE Institute seeks to motivate the investments required to continue Re-X research and technology maturation activities necessary to ensure widespread adoption by U.S. manufacturers.

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 challenging to meet, and why. Update list of high-priority activities for the REMADE Institute to pursue in years two to five to achieve the REMADE Institute 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 Institute 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

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

- **Conduct a systems analysis case study** study for polyethylene terephthalate (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 2022 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 EOL
- **Develop analysis tools** to help design engineers evaluate the trade-offs between initial production cost and the revenue stream at EOL
- **Pilot design for Re-X tools that could be integrated with CAD systems** (and required databases) to guide design engineers on preliminary design best practices and 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 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 reduce scrap generation (increase material efficiency) and directly reuse scrap generated during manufacturing
- **Integrate sensing technologies** that provide real-time automated monitoring and control of key manufacturing processes 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

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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 2022 Technology Roadmap update.

Remanufacturing and End-of-Life Reuse

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

- **Develop technologies for identifying** latent faults associated with mechanical defects in printed circuit boards (PCBs)
- **Explore novel non-destructive evaluation (NDE)** assessment methods for identifying damage in metals
- **Integrate sensor technologies and ML/AI methods** to eliminate the need for destructive testing and enable rapid assessment of the quality of component repair/restoration processes

Thrust Area: **Remanufacturing Analysis Tools & 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 a condition assessment system** for PCB reuse/remanufacturing decision support
- **Develop a framework** for assessing reuse of electrical components and chips on PCBs
- **Develop ML/AI tools and methods to automate non-destructive inspection/evaluation** of cores (products returned for remanufacturing) and components (individual parts within the core)*

Thrust Area: **Low-Cost Component Repair Technologies & Restoration Methods**

- **Integrate REMADE Institute 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 2022 Technology Roadmap update.

Recycling & 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 or 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-scrap 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 low-cost and energy-efficient chemical recycling technologies** 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 and apparel
- **Develop chemical or solvent-based approaches** for removing pigments from polymers

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

- **Develop cost-effective and 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 2022 Technology Roadmap update.

Next Steps

The 2022 revisions improve the specificity and organization 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 –to achieve the goals and TPMs of the REMADE Institute.

Because the Technology Roadmap is a forward-looking document intended to guide the REMADE Institute, it will update its Technology Roadmap periodically per its Operational Plan. In addition, 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 TLC will continue the following activities:

- Conduct interviews with REMADE Institute 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.
- Gather additional impact information to prioritize those activities which yield the most significant impact consistent with the REMADE Institute's goals and mission and the priorities of the REMADE Institute's members.

Annual updates will also be critical to ensure that the REMADE Institute 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

REMADE Institute Technical Performance Metrics (TPMs)

The DOE 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 five years.
- To train an advanced manufacturing workforce.
- To enrich the innovation ecosystem.
- To strengthen U.S. manufacturing competitiveness.
- 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 DOE 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 50 percent (50%) improvement in embodied-energy efficiency within 10 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 a 30% Increase in the Recycling/Reuse Rate**
  Research, develop, and demonstrate improved recycling and reuse in materials manufacturing to enable a thirty percent (30%) absolute increase in recycling rates of specific energy-intensive materials as a prioritized portfolio of technologies.

- **Demonstrate a 20% Reduction in associated Green House Gas emissions (GHGs) and a 10x Reduction in Primary Feedstock Use**
  Improved Material Efficiency and Decreased GHG Emissions: Research, develop, and demonstrate at a 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 percent (20%) lower GHG emissions ($MMTCO_2E$[6]/kg) relative to commercial state-of-the art at the relevant production rate (kg per day).

- **Demonstrate a 30% Secondary Feedstock Increase and a 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 the reuse of recycled and recovered materials to serve as cost-effective material feedstocks for one or more different industries.

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

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[6] Million metric tons (tonnes) of carbon dioxide equivalent

Appendix B

Establishing the 5-year Technical Performance Metric (TPM) Goals and Analyzing the Impact of Research Activities & the Technology Portfolio

▶ TPM Opportunity Analysis

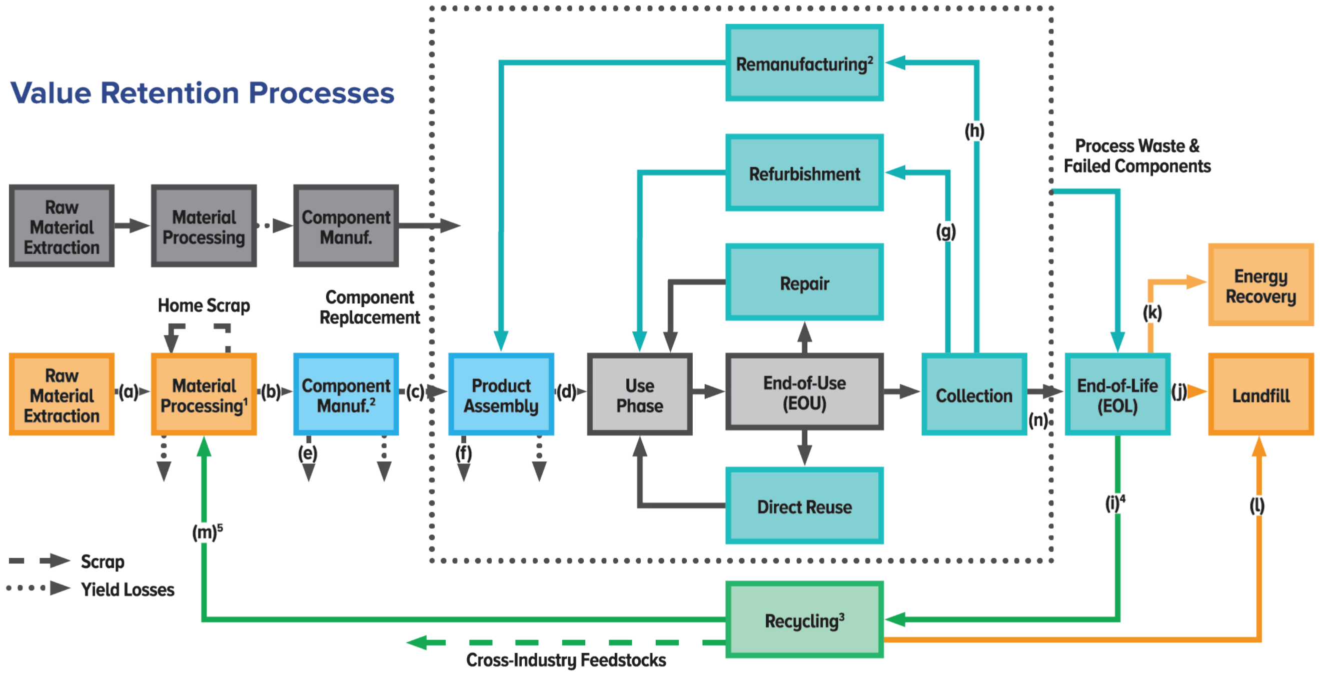
As part of the 2019 Technology Roadmap update, the REMADE Institute conducted a TPM Opportunity Analysis to identify the “areas of greatest opportunity” for each material class and Node. The objectives of this analysis were to:

- 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 each Node would contribute toward achieving the REMADE Institute’s TPMs.
- Establish a framework for allocating REMADE Institute funding to each Node to achieve the TPMs.

The REMADE Institute analyzed each material class's flows and embodied energy. Using the various stages of the materials life cycle and the questions listed in Figure 6 as a framework, the REMADE Institute sought to identify specific opportunities to impact the TPMs relevant to each of the five Nodes and quantify the impact of those opportunities. In addition, the opportunities associated with remanufacturing were evaluated based on a manufacturing sectoral analysis and the current and projected remanufacturing intensity in each sector.

The opportunities the REMADE Institute identified and quantified came from two sources. First, the team analyzed broad themes instead of specific research projects. Two examples of broad themes are the recovery of polymers and metals from e-scrap and the recovery of PET from textiles (clothing and carpet). Second, the REMADE Institute surveyed members to identify technology development opportunities to include in the analysis.

Based on the analysis, the five-year TPMs the REMADE Institute established for the technology R&D portfolio are as follows: 1) a reduction in embodied energy of 1018 Petajoules per year (PJ/yr), 2) a reduction in primary materials use of 41.2 million metric tons (tonnes) (MMT)/yr, 3) an increase in secondary materials use of 41.2 MMT/yr, and 4) a reduction in GHG Emissions of 51.2 MMTCO$_2$E per year.



(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 combused 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?

Figure 6: Framework Used to Evaluate the Areas of Greatest Opportunity and TPM Impacts

▶ Technology Portfolio Impact Analysis

The REMADE Institute conducts a Technology Portfolio Impact Analysis after each RFP and every quarter to measure its progress toward achieving the RPMs. Figure 7 illustrates the process used to estimate portfolio impacts.

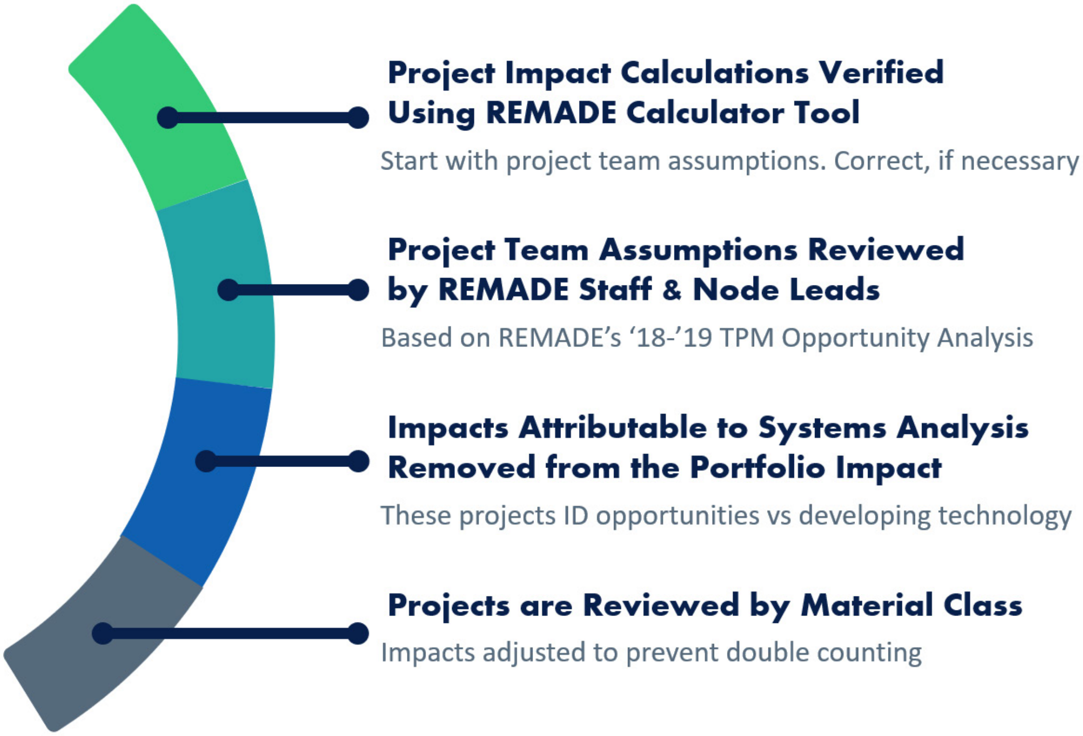


Figure 7: Process Used to Estimate REMADE Institute Technology Portfolio Impacts

One requirement for teams that submit proposals in response to an RFP is to estimate their TPM Impacts. The REMADE Institute developed a Project Impact Calculator to assist with these calculations. In addition, to ensure that the REMADE Institute selects the most impactful projects, the project managers, the Node Leads, and the CTO review each proposal team's assumptions and calculations during the merit review process.

After selecting projects for each RFP, the project managers integrate the TPM impacts from the RFP with the TPM Portfolio Impact estimates for other projects the REMADE Institute has funded. As part of this exercise, the project managers remove the TPM impacts for the Systems Analysis & Integration node projects because they identify opportunities to impact the TPMs. However, they do not develop the technology to realize those opportunities. In addition, the project managers review the TPM impacts for each material class to prevent double-counting TPM impacts for projects that address the same material classes.

To provide the most realistic estimate of technology portfolio impacts, the project managers reassess TPM impacts after each project ends and adjust them depending on whether the project delivered more or less TPM impact than initially estimated. The REMADE Institute provides DOE updated TPM impact estimates in its quarterly report.

Appendix C

Methodology to Establish the Impact, Importance, and Prioritization of Research Activities

In the 2018 Technology Roadmap, the TLC designated a subset of research activities for each Node as "high-priority." The TLC combined several factors to make this determination: participant voting conducted during the Technology Roadmap workshop, expert interviews, and the importance of the research activity to follow-on activities within the REMADE Institute research portfolio. Much of this analysis was qualitative, particularly for the Systems Analysis & Integration and Design for Re-X research activities.

While updating the 2019 Technology Roadmap and Strategic Investment Plan (SIP), the REMADE Institute identified the "areas of greatest opportunity" to meet the TPMs for each material class and Node. Appendix B details the REMADE Institute's methodology to estimate "areas of greatest opportunity," which it publishes yearly in its SIP update.

In parallel, the TLC modified the layout of the research activities. They added start and end dates to each research activity and laid them out as a Gantt Chart. The TLC also consolidated research activities into the 13 Technical Thrust Areas outlined in the Introduction.

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

Impact versus the TPMs

The extent to which a research activity will help the REMADE Institute meet its TPMs. To calculate impact, the REMADE Institute considered two factors:

- The mid-term (first five years of the REMADE Institute) energy, emission, and feedstock consumption impact the REMADE Institute calculated while analyzing areas of greatest opportunity to meet the TPMs,
- TPM impacts the REMADE Institute calculated for projects recommended from the first three 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 Institute's Research Portfolio

The extent to which an activity is foundational to future work the REMADE Institute anticipates pursuing. To calculate importance, the REMADE Institute considered whether an activity is:

- A key enabler for other research activities (The REMADE Institute must accomplish it first), or

- Essential to do despite the lack of easily quantified TPM impacts, which would be the case for most of the Systems Analysis and Design for Re-X research activities.[7]

▶ Probability of Success

An estimate of the relative difficulty of accomplishing an activity compared to other activities. To calculate the Probability of Success, the REMADE institute considered whether an activity:

- Could be accomplished with the initial $70 million DOE provided the REMADE Institute under the cooperative agreement.

The REMADE Institute used the same methodology for research activities it added to the 2020 and 2022 Technology Roadmap updates.

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[7] As part of the 2019 Technology Roadmap update, we initial established the impact criteria based on embodied energy savings. Because the REMADE Institute considers the embodied energy savings for Systems Analysis & Integration Node projects to be zero, none of the Systems Analysis & Integration projects would have fared well when allocating funding from RFPs. To account for this, the TLC developed a parallel criteria, “Importance,” for these types of projects and projects that are early in a sequence of activities that would need to completed before another technology project could start. For example, the REMADE Institute originally intended to develop an LCA tool based on one of the foundational projects. In order for the REMADE Institute to conduct a TPM opportunity assessment, the Institute first needed a tool or method to assess impact vs the TPMs. When the REMADE Institute did not fund the Foundational Project to develop this tool, the REMADE Institute developed its own Project Impact Calculator.

Appendix D

Development of the Original (2018) REMADE Institute Technology Roadmap and the 2019 and 2020 Technology Roadmap Updates

The REMADE Institute's TLC coordinated the development of the Technology Roadmap. They also identified the topics for the first Project Call. The critical 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 TLC and Nexight Group integrated the workshop results with additional inputs from surveys, (SME) interviews, and other relevant documents, including existing roadmaps. During the 2017 technology roadmapping process, workshop participants, the TLC, and the DOE Advanced Manufacturing Office (AMO) reviewed the workshop report and intermediate Technology Roadmap drafts prepared by the TLC and Nexight Group to refine the content further. Figure 8 summarizes the entire process.

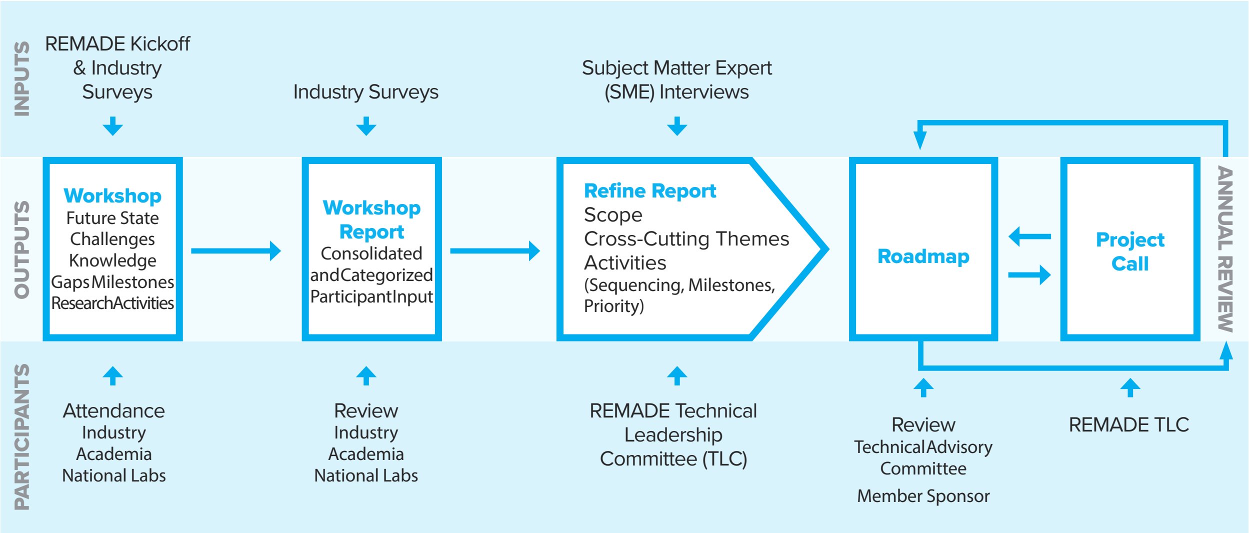

Figure 8: Institute Development Process for the Original (2018) REMADE Institute Technology Roadmap

▶ Activities Before the Technology Roadmapping Workshop

The REMADE Institute began framing its Technology Roadmap at a proposal workshop held in Denver, CO, in August 2016. Participants from industry, academia, national laboratories, and trade associations identified critical challenges faced in reaching the TPMs outlined in the REMADE Institute Funding Opportunity Announcement (FOA). At the REMADE Institute Kick-off Meeting held in Rochester, NY, June 19–20, 2017, participants attended break-out sessions organized by Node to review the barriers from the August 2016 workshop and identified additional technical obstacles.

▶ 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 EOL reuse, and recycling and recovery, which were sent to industry stakeholders. In each survey, participants were asked to identify, from a broad list, the critical barrier impacting their industry and provide additional information about which REMADE Institute-relevant material classes this barrier affected and whether the impact was financial or technical. Because the REMADE Institute developed the surveys using the Crowdoscope collective intelligence tool, participants could also review and anonymously comment on responses from other participants. Unfortunately, there was limited initial survey participation before the technology roadmapping workshop due to the time between the surveys' release dates and the workshop.

▶ Technology Roadmapping Workshop

Following the workshop, Nexight Group prepared a summary report of the key findings, 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. The REMADE Institute asked them 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 workshop participants did not adequately address due to a lack of specific industry participation. The TLC identified and interviewed SMEs from the pulp and paper industry to ensure that 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 the REMADE Institute
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 developed during the roadmapping workshop, to identify research activities that would best enable the REMADE Institute to achieve its TPMs and deliver impact to U.S. manufacturers. In addition, the REMADE Institute prioritized information provided by industry over feedback from universities and national labs. The TLC then organized research activities into a logical sequence of activities by year and difficulty level involved. In cases where there were gaps between the various research 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 the TLC and key DOE-AMO staff reviewed. Next, the TLC edited the technology roadmap. AMO then reviewed the new draft and provided comments to the TLC. Following multiple rounds of TLC edits and AMO reviews, the REMADE Institute provided workshop participants and members of the REMADE Institute's TAC with a draft public version of the roadmap for comment. Finally, based on feedback, the REMADE Institute released a final public draft of the Technology Roadmap for comment.

2019 Technology Roadmap Update

The TLC updated the 2019 version of the Technology Roadmap using the process summarized in Figure 9, including 1) structured interviews with numerous REMADE Institute industry members who may 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 Institute's TPMs, 3) TLC assessment of the Probability of Success and Importance to the REMADE Institute's Research Portfolio associated with the various R&D topics, 4) informal discussions with REMADE Institute members at the Annual Meeting and through other venues to validate the results of the analyses, and 5) feedback provided by the REMADE Institute's TAC, SAC, and GB.

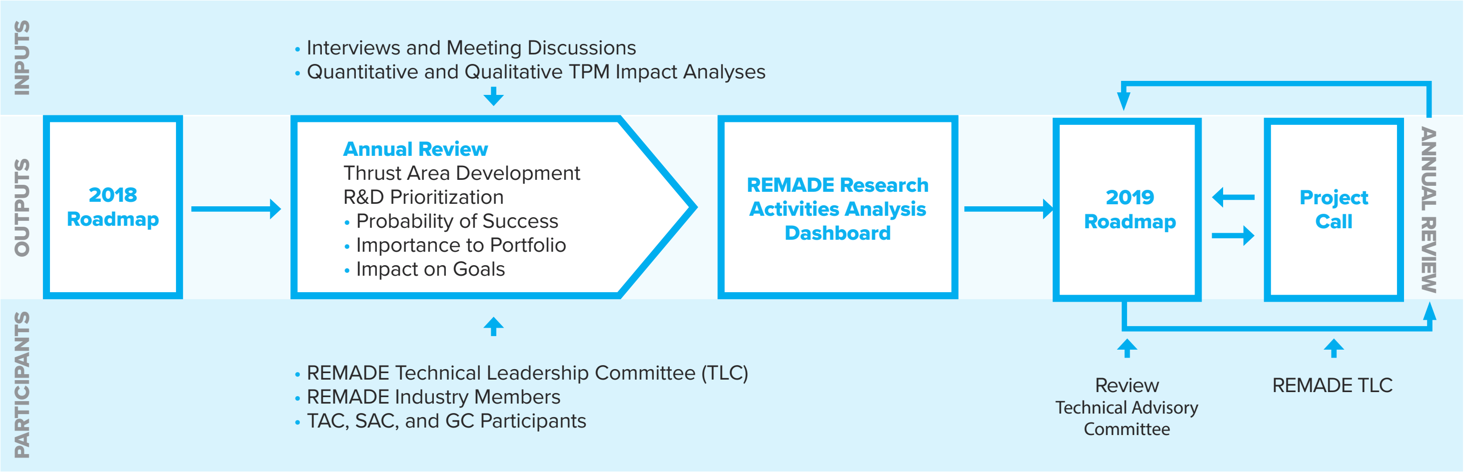

Figure 10: 2019 Roadmap Revision Process

To improve the readability of the Technology Roadmap and accelerate the development and release of RFPs, the TLC made multiple changes in preparing the 2019 REMADE Institute Technology Roadmap. First, the TLC added start and end dates to the research activities and consolidated them into 13 Technical Thrusts Areas, with assistance from the TAC. The TLC organized each Thrust Area as a sequence of research activities displayed as a Gantt chart. The TLC introduced these modifications to help members develop proposal concepts and form teams in anticipation of upcoming project calls.

The REMADE Institute and Nexight Group also modified the layout of the roadmap and created an Analysis Dashboard. To begin, the TLC mapped each research activity based on the following criteria: Impact versus the TPMs, Importance to the REMADE Institute's Research Portfolio, and Probability of Success. Nexight Group used this information to create 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-scrap.

As part of the 2019 Technology Roadmap update, the TLC removed the EWD activities and placed them into a stand-alone EWD Roadmap. This allowed the EWD Director to describe the REMADE Institute's three-tiered structure for organizing and delivering training products: Overview and Awareness Training, Short Course Modules, and REMADE Institute Professional Certificates. The EWD Roadmap also identifies course content the REMADE Institute will develop.

Development of the First and Second Project Calls

In parallel with the development of the Technology Roadmap, the TLC identified and prioritized topics for the first and second project calls using the process outlined in Figures 8 and 9.

2020 Technology Roadmap Update

The TLC developed the 2020 Technology Roadmap Update using the process summarized in Figure 10, which included the following actions: 1) Analysis of the REMADE Institute project portfolio to identify gaps in coverage by material class and focus area, 2) Quantitative analysis to evaluate progress toward meeting the REMADE Institute TPMs for embodied energy, primary and secondary feedstock consumption, and emissions, 3) Virtual break-out sessions the TLC and project managers hosted during the 2020 Technology Summit to validate the status of previously identified high-priority research activities and identify new high-priority topics to add the Technology Roadmap, 4) Design for Re-X discussions held with industry and trade association members to identify which design topics the REMADE Institute should address, and 5) the REMADE Institute's TAC, SAC, and GB feedback. Like prior iterations of the REMADE Institute Technology Roadmap, the TLC used the 2020 Technology Roadmap to identify research priorities in the REMADE Institute's fourth RFP.

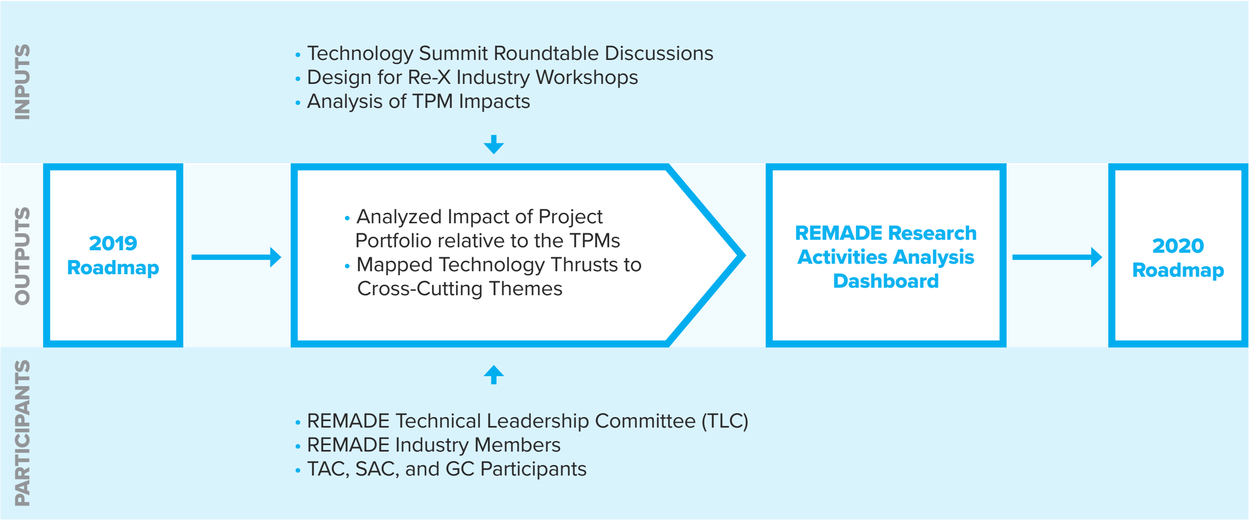

Figure 10: 2020 Roadmap Revision Process

Appendix E

Technology Roadmap Contributors

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

NAME	ORGANIZATION
Magdi Azer	REMADE Institute (Chief Technology Officer)
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Bob Winskowicz	Sterilis
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Appendix F

Background Information on the Request for Information (RFI) and Industry Interviews

On January 21, 2022, the REMADE Institute released an RFI to solicit feedback from interested individuals and entities, such as industry, academia, research laboratories, government agencies, and other stakeholders, to ensure: 1) the REMADE Institute's Technology Roadmap continues to address the most critical opportunities and pressing challenges associated with increasing the recovery, reuse, remanufacturing, and recycling of metals, fibers, polymers, and electronic waste, and 2) the REMADE Institute's strategy for self-sustainment focuses on addressing the most pressing national needs and challenges related to reducing the embodied energy and carbon emissions associated with industrial-scale materials production, processing, and EOL disposition.

The RFI consisted of two sections that addressed the Technology Roadmap and the path to self-sustainment, respectively. Each section addressed four categories: Strategy, Technology, Partnerships, and Workforce Development & Training. This appendix summarizes the RFI responses regarding the Technology Roadmap and the industry member interview feedback. Together, they form the basis of the technology roadmap updates presented in the main body of this document.

▶ RFI Feedback Relevant to the Technology Roadmap

The TLC compiled a high-level summary of RFI feedback. An overview of comments relevant to the Technology Roadmap, organized by broad themes and focus areas (Node), includes the following:

Technology (General Comments):

- Rapid feedstock/material characterization is an area the REMADE Institute has not addressed (ties to the materials-related comment regarding properties for secondary feedstocks).
- Machine learning has many applications relevant to the REMADE Institute.

Materials-related Comments:

- To encourage designers to use recycled content in their designs, they need better information regarding how material properties change as secondary feedstock content increases.
- Durable goods like mattresses, carpets, appliances, and furniture often go into MSW– more attention needs to go into these products.

Supply Chain/Markets-related Comments:

- The REMADE Institute should focus more on the cost side of the TPMs, "Demonstrate Potential for Cost Parity for Secondary Feedstocks and Energy Parity for Secondary Feedstocks."
- The REMADE Institute must also address the cost of recycled materials relative to primary materials (beyond the REMADE Institute). Tools to help manufacturers better understand these trade-offs would be helpful to sustainability.
- Manufacturers are reluctant to use secondary feedstock because of concerns that they will not be able to acquire reliable quantities of high-quality recycled materials required to meet minimum performance targets. These concerns are amplified for applications where manufacturing volumes are large, and they would need to retool to use recycled materials.

- Where consumption of secondary plastics has grown significantly, the recycling industry needs to identify ways to recover more plastic.

Systems Analysis & Integration Node:

- The Systems Analysis & Integration node should look to synthesize the data from the other nodes into integrated tools that industry members can use.
- Regarding the development of the LCA tool – As indicated in the letter, we would discourage the REMADE Institute from allocating time and resources to develop a new LCA tool. Many commercial databases and LCA tools are available, and we do not need a new one.

Design for Re-X Node:

- Design for recycling could use more projects in flexible electronics (separatable substrates, biodegradable materials). In addition, the design of plastic products using sustainable resins (e.g., secondary feedstock content, biobased/biodegradable resins) would benefit the REMADE Institute.
- There is insufficient data around Design for Re-X, including carbon footprint data, recycled content or recyclability information, or rules for Serviceability.
- The REMADE Institute should address clean energy technologies such as photovoltaics (PV) and wind turbines from a life-cycle perspective focusing on design, remanufacturing, and recycling.

Manufacturing Materials Optimization Node:

- The REMADE Institute should focus on reducing primary material consumption by improving material efficiency and reducing waste rather than increasing secondary feedstocks to offset primary production.
- Industry-wide standards are lacking for secondary feedstock.

Remanufacturing & End-of-life Reuse Node:

- There is an opportunity to do more with wind turbines, including electronics and controls.
- The REMADE Institute should address clean energy technologies such as PV and wind turbines from a life-cycle perspective focusing on design, remanufacturing, and recycling.

Recycling & Recovery Node:

- Chemical recycling needs advancement to reduce energy intensity and the required scale of implementation.
- The REMADE Institute should emphasize increasing the collection and sorting of plastics.
- The REMADE Institute should address clean energy technologies such as PV and wind turbines from a life-cycle perspective focusing on design, remanufacturing, and recycling.
- Improvements to collecting and processing materials are needed to offset the increased demand for secondary feedstocks.
- There could be more emphasis on evaluating the effect of ultraviolet (UV) coatings and printing on the properties of recycled PE films.

Industry Member Interviews

To further refine the feedback received in response to the RFI released in January 2022, the REMADE Institute contacted 30 member companies that had responded to RFI to schedule follow-up interviews. These companies represented all the REMADE Institute-relevant material classes and membership tiers. Of this list, 12 companies responded, including large multinationals and small and medium-sized companies.

The REMADE Institute conducted these interviews in the spring of 2022. To begin, the interviewers asked companies to identify a single project or technology development effort they wanted the REMADE Institute to tackle on their behalf and whether they would be interested in executing a joint REMADE Institute project with companies facing similar issues.

In preparation for the release of RFP 6, the REMADE Institute interviewers also asked interviewees to identify whether they had participated in projects. For those who responded yes, the interviewers asked the respondents to determine which projects would make good technology demonstration projects and whether their company would be interested in serving as a technology demonstration site. Finally, the interviewers asked each company what the REMADE Institute could do to promote its EWD projects to their employees and whether there was an EWD course or tiered certificate pathway they wanted to see the REMADE Institute develop. The specific questions posed to the companies included the following:

1. If you responded to the recent RFI, are there any items you would like to discuss or highlight from your response? If so, what are they?
2. How well does the REMADE Institute Technology Roadmap capture your company's concerns and the issues you face?
3. What is one technical/economic issue that you would like to see the REMADE Institute tackle on behalf of your company?
    - If the REMADE Institute could identify a group of companies facing similar issues, would you be interested in executing a joint REMADE Institute project?
4. Is there a project you have participated in that would make a good technology demonstration project? If so, which one?
    - If this were to become a project, would your company be potentially interested in serving as a technology demonstration site
5. How can the REMADE Institute help promote our EWD online courses, including tiered certificate pathways, to your employees?
    - Is there an EWD course or tiered certificate pathway you would like to see the REMADE Institute develop? If so, what is it?

Utilizing the same categories used to summarize the RFI feedback, the interviews provided the following feedback relevant to the technology roadmap.

Technology (General Comments):

- Artificial Intelligence
    - The Institute should promote the development of commercially viable AI applications.
    - Increase the robustness of AI for different applications beyond defect detection.

- Identify ways digital tools can support circular economy solutions.
- Data
  - Digital technology has a crucial role, but how do you weigh variables – machine learning, AI, data mining, data science/analytics?
  - Along similar lines, is information from MRFs consistent?
  - Creation of data sets to test and train new AI algorithms
- Digital tracking and tracing of packaging
- More projects like MRFF
- Electric vehicles

Materials-related Comments

- Increase the recycling rate of PET thermoforms
- Chemical recycling of polyester and cotton
- Polyester
  - Creating a cross-industry circular economy for this material
- Increasing recovery, recycling, and circularity of polyolefins, rubber, and leather
- Increasing the supply of secondary PET, high-density polyethylene (HDPE), and polypropylene (PP)
- Establishing circular flows for Ethyl-vinyl-acetate (EVA) and rubber
- Increasing collection and processing of flexible films and multilayer flexible packaging

Supply Chain/Markets-related Comments:

- The use of digital tools to optimize or model processes in supply chains
- How do you size operations at a reasonable scale for markets and investment strategies in a community to maximize profit sustainably?
- Use material flow analysis to identify opportunities to establish a circular economy for REMADE Institute-relevant materials
- Increase sourcing and utilization of recycled content in products
- Reverse logistics for recycling apparel

Systems Analysis & Integration Node:

- How do you optimally balance the use of advanced and mechanical recycling technologies?
- Create a map of material flows to help companies understand where to send waste to be recycled.
- Aggregate material flow data and other data to create training data sets for AI applications.

Design for Re-X Node:

- Design for reuse and remanufacturing
- Design for recyclability to balance the front (design) and back (recycling) end for a particular material stream.
- Design for recycling solar panels and textiles.

- Increase the manufacturability of mobility systems –EVs and internal combustion engine vehicles (ICEVs) – through design.

Manufacturing Materials Optimization Node:

- E-scrap - removal of batteries from older technology tablets.
- Solar panels
- Creation of recycling certificates or passports to track the pedigree of different feedstocks throughout their lifecycle

Remanufacturing & End-of-life Reuse Node:

- Additive manufacturing technologies to repair components during remanufacturing
- Remanufacturing of tires and tracks
- Energy storage – how to handle used battery returns – salvage versus reuse, safety
- Assessing the remaining life of components before crack initiation

Recycling & Recovery Node:

- Collection and sorting

  - For sorting, one concern is the interplay between sorting and preparation of feedstocks. Specifically, do the sorting requirements change if one is using mechanical recycling versus chemical or solvent-based recycling?

  - How do we develop more-economical sensors that can sort at scale?

  - Development/advancement of mechanical/automated sorting of aluminum scrap to provide a purer aluminum scrap stream

  - Collection and separation (disassembly) of apparel

  - Increasing diversion rates of waste streams to facilitate increased secondary feedstock availability

- Handling contaminants and potential process byproducts
- Characterization of the chemical/microscopic composition of scrap plastics for mechanical recycling of food contact plastics
- Chemical and solvent-based recycling

  - What are this technology's actual energy and emissions impacts, and does it genuinely provide net energy and emissions benefits?

  - How can we implement chemical recycling on a larger scale than current demonstration projects?

  - Are disruptive technologies required to implement this technology at scale?

- Standardization and certification of secondary feedstocks, particularly regarding food contact?
- Deinking of textiles

Appendix G

Process the REMADE Institute Used to Translate RFI and Industry Interview Responses into 2022 Technology Roadmap Updates

This appendix discusses how the REMADE Institute used the information it collected from the RFI responses and the one-on-one industry interviews to update this technology roadmap, details the changes made in the 2022 Technology Roadmap update, and explains the rationale behind these changes. This appendix also explains how these changes will improve the REMADE Institute's ability to achieve its goals and TPMs.

Three motivating factors influenced the changes the TLC made in the 2022 Technology Roadmap Update:

1. A desire to clarify research activities from the 2020 version of the Technology Roadmap that overlap with other research activities
2. Responding to RFI and industry interview responses, the REMADE Institute collected
3. Emerging technology and market trends that could influence REMADE Institute research activities

▶ Clarifying Research Activities

In the 2022 Technology Roadmap Update, the TLC edited research activity 5.03 from the 2020 Technology Roadmap to clarify its focus and avoid overlap with other research activities. This research activity suggested three avenues to improve process yields and reduce defects when manufacturers use secondary feedstocks: 1) modifying existing processes, 2) developing new manufacturing processes, or 3) performing process simulations. When the TLC reviewed the roadmap for potential changes, they saw that research activities 6.09 and 6.10 already addressed existing processes and new process development, respectively. Therefore, the TLC narrowed the focus of research activity to performing process simulations.

▶ Responding to RFI & Industry Interview Feedback

To help manage the RFI and industry interview feedback, the TLC organized input from both sources into eight categories: technology, materials, supply chain/markets, and the five Nodes. First, the TLC looked for where RFI respondents and interviewees provided similar feedback in a single category, such as technology. The TLC then identified keywords/cross-cutting themes that emerged from more than one node and in more than one category and compiled relevant feedback for the 13 themes that emerged.

▶ Identifying Emerging Technology & Market Trends

The recycling community has developed a term, "the Evolving Ton," to illustrate how the waste that flows into MRFs has changed and continues to change over time. An example of the evolving ton is the transition from glass containers and steel cans to lighter packaging materials. Similarly, global trends, such as increased concern with climate change, have motivated a transition from fossil-based energy production toward clean energy technologies.

In updating the Technology Roadmap, the TLC evaluated emerging technology and market trends affecting the design, manufacturing, remanufacturing, and recycling industries. Technology and market trends likely to impact metal, polymer, fiber, and e-scrap material flows were also considered. Two trends, aligned with the RFI and industry interview feedback, emerged. First, the U.S. industry continues to adopt

ML/AI to increase productivity, reduce material losses, and optimize supply chains[8]. Second, increased installation of clean-energy technologies, such as solar PV, wind turbines, and EVs, will impact REMADE Institute-relevant material consumption.[9]

Finally, the TLC compared the RFI and industry feedback and emerging technology and market trend data against the current technology roadmap and technology portfolio to identify gaps that needed to be addressed. For example, as Tables 6-10 demonstrate, some roadmap changes involved adding new research activities, such as "Develop repair restoration processes for wind turbine generators and drive trains and high-value EV cores and components." Alternately, some research activity updates involved modifying research activities to incorporate RFI and industry feedback. One example is research activity 8.06, "Develop **ML/AI tools and methods to automate the non-destructive inspection** of cores (products returned for remanufacturing) and components (individual parts within the core)."

Changes Incorporated in the 2022 Technology Roadmap Update and the Rationale Behind Those Changes

Tables 6-9 contain modifications or additions to the research activities the TLC made in the 2022 Technology Roadmap update. In each table, the TLC has identified the corresponding research activity number and their rationale for making the change.

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[8] According to the World Manufacturing Foundation, manufacturers will increase the adoption of ML/AI from $2.9 billion in 2018 (*2020 World Manufacturing Report: Manufacturing in the Age of Artificial Intelligence*) to $13.2 billion in 2025

[9] By 2050, more than 40% of the world's current aluminum production will be required to mount and install solar panels (*https://www.sciencealert.com/solar-panel-boom-s-demand-for-aluminium-is-a-big-carbon-problem*)

Table 6. Changes Made to Systems Analysis & Integration Node Research Activities in the 2022 Technology Roadmap Update

Research Activity #	SYSTEMS ANALYSIS & INTEGRATION	
	RESEARCH ACTIVITY CHANGE	RATIONALE FOR THE RESEARCH ACTIVITY CHANGE
1.09 ('20 Roadmap)	Eliminated this research activity because it was to have integrated MFA/LCA tools and data with existing/emerging design tools, and the target application was a Foundational Design for Re-X project the REMADE Institute did not fund	The REMADE Institute did not fund the Foundational Design for Re-X Project that was to have used the MFA/LCA data. Also, RFI respondents noted that many good LCA tools and databases exist today
1.10 ('20 Roadmap)	Eliminated this research activity because REMADE Institute did not fund the Foundational Systems Analysis & Integration Project that would have developed the LCA Tool	The REMADE Institute did not fund the Foundational Project to develop this LCA Tool. Also, RFI respondents noted that many good LCA tools and databases exist today
2.09 ('20 Roadmap)	Eliminated this research activity because REMADE Institute did not fund the Foundational Design for Re-X Project that would have leveraged the data needs analysis work associated with this research activity	REMADE Institute did not fund the Foundational Design for Re-X Project (or only funded it much later with a significantly smaller work scope) that would have leveraged the data needs analysis work

Table 7. Changes Made to Manufacturing Materials Optimization Node Research Activities in the 2022 Technology Roadmap Update

Research Activity #	MANUFACTURING MATERIALS OPTIMIZATION	
	RESEARCH ACTIVITY CHANGE	RATIONALE FOR THE RESEARCH ACTIVITY CHANGE
5.01	Clarified that feedstock and material characterization techniques need to be faster than those available today	RFI respondents indicated the need for ”rapid” feedstock/characterization techniques
5.03	Divided a research activity focused on improving process yields and reducing defects when one uses secondary feedstocks into two separate actions. The first activity focuses on using process simulations to guide process development. The second activity deals with using machine-learning (ML) and artificial intelligence (AI) tools and techniques to modify existing processes or guide manufacturing process development[10]	Tasks 6.09 and 6.10 already deal with existing processes and the development of new processes, respectively. This research activity only uses process simulations to improve yields and reduce defects
6.05	Modified a research activity focused on developing process technologies to increase secondary feedstock content and reuse scrap generated during manufacturing into one where manufacturers use primary feedstocks more efficiently	RFI respondents noted that rather than only focusing on increasing secondary feedstock use, the REMADE Institute could accomplish the same objective by reducing scrap generation (increasing material efficiency) and directly reusing scrap
6.08	Narrowed the focus of a materials development-related research activity to developing materials more tolerant of variations in secondary feedstock composition	Research activity 6.09 already addresses adjusting processes to accommodate variations in secondary feedstocks. The TLC changed the focus of this research activity to developing more tolerant materials
6.09	Broadened the scope of one research activity focused on making real-time process adjustments to include cross-industry feedstocks. The previous focus was limited to secondary feedstocks	Research activity 6.09 is now consistent with 6.10. Both address secondary and cross-industry feedstocks
6.10	Narrowed the scope of this research activity to solely focus on guiding manufacturing process development because research activity 6.09 already addresses real-time process adjustments.	Research activity 6.09 already addresses real-time process adjustments
6.12	Moved a research activity focused on improving the collection and sorting of wrought metals to the Recycling & Recovery Node and broadened the scope to include all metals	Collection and sorting tasks are the purview of the Recycling & Recovery Node

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[10] Numerous RFI respondents encouraged the REMADE Institute to leverage existing or emerging ML/AI techniques to increase reuse, remanufacturing, recovery, and recycling.

Table 8. Changes Made to Remanufacturing & End-of-life Reuse Node Research Activities in the 2022 Technology Roadmap Update

Research Activity #	**REMANUFACTURING & END-OF-LIFE REUSE**	
	RESEARCH ACTIVITY CHANGE	**RATIONALE FOR THE RESEARCH ACTIVITY CHANGE**
7.03	Broadened the scope of one research activity to develop an in-process method for NDE of thermal-sprayed coating to focus on eliminating the need for destructive testing and enabling rapid assessment of the quality of component repair/restoration processes. The approach suggested in the new research activity is to integrate sensor technologies and ML/AI methods to achieve this goal	The goal of developing the in-process method for NDE of thermal-sprayed coating was to replace a destructive testing method with a non-destructive method. The REMADE Institute has funded the larger goal of rapidly assessing component restoration/repair processes. In addition, the TLC added sensor technologies and ML/AI integration based on RFI feedback
7.04 ('20 Roadmap)	Moved this research activity to Technical Thrust Area 8.0	The research activity focuses on tools and methods rather than evaluation techniques
7.04 (was 7.05)	Included the integration of ML/AI tools and methods into a research activity focused on developing low-cost inspection techniques to characterize contaminants and rapidly assess part cleanliness, both before and after cleaning	The original focus of this research activity was to characterize contaminants and rapidly assess the cleanliness of parts to be remanufactured. The TLC broadened this to include inspection of cleanliness after remanufacturing, which came from the original roadmap feedback. In addition, per RFI feedback, the TLC added the integration of ML/AI tools and methods
7.07 (NEW)	Added a new research activity to develop condition assessment methods for wind-turbine generators and drive trains	Based on RFI and industry feedback to focus on solar PV, wind turbines, EV cores and components, and clean energy technologies, the TLC added this research activity to develop condition assessment tools
8.06 (NEW)	Expanded the scope of research activity to develop automated approaches for assessing/ inspecting the condition of cores to include the development of ML/AI tools and methods to achieve this goal	Based on RFI and industry feedback to leverage ML/AI tools and methods more, the TLC expanded the scope to include developing ML/AI tools and methods
9.07	Added a new research activity to develop processes to repair wind-turbine generators and drive trains and high-value EV cores and components cost-effectively	Based on RFI and industry feedback to focus on solar PV, wind turbines, EV cores and components, and clean energy technologies, the TLC added this research activity to develop condition assessment tools

Table 9. Changes Made to Remanufacturing & End-of-life Reuse Node Research Activities in the 2022 Technology Roadmap Update

Research Activity #	RECYCLING & RECOVERY	
	RESEARCH ACTIVITY CHANGE	RATIONALE FOR THE RESEARCH ACTIVITY CHANGE
10.04 (NEW)	Added the manufacturing node research activity to improve the collection and sorting of wrought metals to this node and broadened the scope to include end-of-life materials rather than metals	Formerly task 6.12
10.05 (NEW)	Added a new research activity focused on using ML/AI to improve ID, separation, and recovery of materials flowing through MRFs	Based on RFI and industry feedback to leverage ML/AI tools and methods more, the TLC expanded the scope to include applying ML/AI tools and methods to improve ID, separation, and recovery of materials flowing through MRFs
10.06 (NEW)	Added a new research activity focused on developing reverse logistics tools necessary to increase the collection and recovery of end-of-use and end-of-life materials	The feedback from an industry interview was for the REMADE Institute to develop reverse logistics tools for recycling apparel. Given the importance of reverse logistics, the TLC broadened to apply to remanufacturing
11.08 (NEW)	Added a new research activity focused on cost-effectively separating metals, polymers, and glass in solar panels and electric vehicles	Based on the RFI and industry interview feedback to view clean energy technologies from a life cycle perspective that includes recycling, the TLC added this task to the roadmap
12.04	Expanded the scope of this research activity to include non-apparel applications and incorporated the requirement that chemical recycling technologies be low-cost and energy-efficient	The 2020 Technology roadmap only mentioned textile and non-textile applications. The TLC modified Task 12.05 to address textiles and apparel. For consistency, the TLC modified research activity 12.04 to include non-apparel and non-textile applications. Also, RFI respondents and interviewees raised questions regarding whether chemical recycling provides net energy and emissions benefits. They suggested that the REMADE Institute update the roadmap to that we seek low-cost and energy-efficient chemical recycling technologies
12.05	Modified this research to activity include apparel applications and incorporated the requirement that chemical recycling technologies be low-cost and energy-efficient	The 2020 Technology roadmap only mentioned textile applications. The TLC modified Task 12.05 to address textiles and apparel based on industry interviewees' feedback. Also, RFI respondents and interviewees raised questions regarding whether chemical recycling provides net energy and emissions benefits. They suggested that the REMADE Institute update the roadmap to that we seek low-cost and energy-efficient chemical recycling technologies
13.01	Added the requirement that characterization methods for assessing and standardizing the composition and quality of secondary material streams must also be rapid	RFI respondents indicated the need for ”rapid” feedstock/ characterization techniques
13.09 (NEW)	Broadened the scope of the research activity to characterize contaminants, including developing ML/AI tools to identify the contaminants and the best end-use of materials based on their contamination level	Based on RFI and industry feedback to leverage ML/ AI tools and methods more, the TLC expanded the scope to include applying ML/AI tools and methods to ID contaminants and the best end-use of materials based on their contamination level

Table 10. Alignment Between 2022 Technology Roadmap Update and the REMADE Institute Goals

Research Activity #	NODE	RESEARCH ACTIVITY	MODIFY AN EXISTING RESEARCH ACTIVITY	NEW RESEARCH ACTIVITY	REDUCE ENERGY EMISSIONS VIA LOWER PRIMARY MATERIAL USE	INCREASE SECONDARY FEEDSTOCK USE	ACHIEVE BETTER THAN COST & ENERGY PARITY	DEVELOP TRANSFORMATOION TECHNOLOGIES	REPRESENTS A MATERIAL STREAM EXPECTED TO EXPAND TO 2050
5.01	MM	Enable rapid material characterization in secondary mat'ls	●			●	●	●	
5.03	MM	Process simulations to lower defects w/ secondary feedstock	●			●		●	
6.05	MM	Decrease reduce primary feedstock manufacturing losses	●		●			●	
6.08	MM	Develop mat'l more tolerant of secondary feedstock variation	●			●		●	
6.10	MM	Utilize ML/AI tools & methods to guide process development	●			●		●	
7.03	RM	Integrate sensors & ML/AI methods to eliminate destructive testing and enable rapid assessment of component repairs	●			●		●	
7.04	RM	Apply ML to characterize contaminants & assess cleanliness	●			●		●	
7.07	RM	Develop condition assessment of wind turbine generator/drives		●		●		●	●
8.06	RM	Develop ML/AI to automate NDE/NDI of cores & components		●		●		●	
9.07	RM	Develop processes to repair wind turbines cost-effectively		●		●	●	●	●
10.04	RR	Improve collection/sorting of EOL mat'ls to preserve the value		●		●		●	
10.05	RR	Apply ML/AI to improve ID, separation, and recovery in MRFs		●		●		●	
10.06	RR	Develop reverse logistic tools to increase the collection & recovery of EOL materials and products cost-effectively		●		●		●	
11.08	RR	Develop tech to separate mat'ls in solar PV/EVs cost-effectively		●		●	●	●	●
12,04	RR	Develop low-cost & energy-efficient Chem Rec non-textiles/ non-apparel	●			●	●	●	
12.05	RR	Develop low-cost & energy-efficient Chem Rec textiles/apparel	●			●	●	●	●
13.01	RR	Develop cost-effective & rapid characterization methods	●			●	●	●	
13.09	RR	Develop ML/AI tools to characterize contaminants in rmat'ls		●		●		●	

Appendix H

Knowledge Gaps that the REMADE Institute Must Address to Overcome the Technical and Economic Barriers for Each Node

Technical and Economic Challenges and Associated Knowledge Gaps for the Systems Analysis & Integration Node

For companies to realize the desired future state of systems analysis and integration tools, methods, and data applicable to Re-X, the research community and industry must work to overcome the following technical and economic challenges:

Energy and emissions data for different materials and processes are unavailable or incomplete.

- LCA data on manufacturing processes is often unavailable, outdated, or based on EE 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 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-or company-specific and are not widely available, which increases the uncertainty of modeling approaches.
- No easily accessible database covers U.S. manufacturing systematically and includes the material requirements (inputs) and the various material outputs at the firm level.
- 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 an insufficient understanding of secondary material markets.

It is challenging to provide guidance and strategic focus for the REMADE Institute's research efforts because existing LCA and materials flow analysis (MFA) information frequently focuses on specific materials or processes and does not consider systems interactions.

- Comprehensive overviews of the quantities and materials employed in U.S. manufacturing are unavailable, limiting the ability to set priorities.
- There is limited understanding of the trade-off effects that material selections may cause across different sectors.

Technical and Economic Challenges and Associated Knowledge Gaps for the Design for Re-X Node

For companies to realize the desired future state of design for Re-X frameworks and tools, the research community and industry must work to overcome the following technical and economic challenges.

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 from designers to provide initial inputs.
- Current design for Re-X tools provide feedback that may be outside 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.

- 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 EOL.
- Business models for Re-X do not make their way into preliminary product conceptualization.

Design engineers are not the ultimate decision-makers regarding the economic benefits of Re-X.

- 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. They may not even involve designers, making it difficult to justify investment in new design for Re-X tools.

Designers are hesitant to specify secondary feedstocks because material property data is frequently unavailable or incomplete. In addition, the extent to which material quality specifications should be adjusted to achieve equivalent performance is not well-defined.

- Industry-wide material property and quality specifications for secondary feedstocks are frequently unavailable.
- Methods to adjust material property and 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 evaluate the 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 or 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 EOL is limited and is often material, geometry, or product-specific, making it difficult to develop tools that multiple industries can use.
- Designers do not have tools for making design decisions that involve trade-offs between initial manufacturing costs and increased Re-X at EOL.

Technical and Economic Challenges & Associated Knowledge Gaps for the Manufacturing Materials Optimization Node

For companies to realize the desired future state of manufacturing materials optimization, the research community and industry must work to overcome the following technical and economic challenges.

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

- Manufacturing processes developed for primary feedstock cannot 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 produced from different materials have not been developed for REMADE Institute-relevant materials.

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

- Techniques for real-time materials characterization 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 unavailable.
- Real-time sensing techniques and analysis capabilities for correcting 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 unavailable.
- 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.

Manufacturers do not effectively utilize material waste from current manufacturing processes 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 regarding waste stream availability and composition remain 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 processes to manufacture net-shaped or functionally gradient materials to reduce embodied energy are unavailable.
- Models for performing embodied energy analysis for manufacturing processes are unavailable or limited to databases that are not widely available.

Technical & Economic Challenges and Associated Knowledge Gaps for the Remanufacturing and End-of-Life Reuse Node

For companies to realize the desired future state of remanufacturing and end-of-life reuse, the research community and industry must work to overcome the following technical and economic challenges.

Lack of robust non-destructive inspection/evaluation techniques for assessing damage limits 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) before cracks develop do not exist.
- Methods to assess the condition of solid-state components and microprocessors in electronics are unavailable.
- In practice, while used circuit boards undergo functional testing for condition assessment, no technologies are available to measure or detect latent defects in used printed circuit boards (PCBs).

There are limited techniques for translating inspection or evaluation data into an assessment of residual value and the remaining life of products and components.

- Most EOL products do not have any associated usage or operational data, making it challenging to assess core value and predict the remaining life of components.
- Existing technologies for assessing core condition or value before disassembly are based on limited data and understanding of the condition of a core 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 most significant opportunity to improve energy efficiency are frequently unavailable 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 minimal.

Remanufacturers have not developed methods for restoring components to "like-new" condition, limiting component reuse in remanufacturing.

- There are no cost-effective technologies for removing the conformal coating or potting from circuit boards, limiting the repair and reuse of circuit boards.
- While light scratches can be polished, there are no cost-effective methods for repairing more serious 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 cannot find reliable sources of used or EOL products because cost-effective approaches for establishing effective reverse logistics networks for new product lines or material reuse opportunities are unavailable.

Technical and Economic Challenges and Associated Knowledge Gaps for the Recycling & Recovery Node

For companies to realize the desired future state of recycling and recovery, the research community and industry must work to overcome the following technical and economic challenges.

The 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-scrap 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 ad hoc rather than relying on theoretical analysis or comprehensive 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 Institute-relevant material, which limits the ability to collect and separate waste streams.

- Logistics models are inadequate for economically integrating waste generation and processing configurations.
- Cross-business collaboration mechanisms to improve recycling and secondary feedstock utilization are not well established.
- Current collection mechanisms cannot 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 collecting, 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 attempting 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 unavailable.
- Methods for identifying and removing hazardous materials and components (e.g., batteries in e-) from waste streams are unavailable.
- Cost-effective technologies for trace contaminants that achieve the required level of cleanliness are not always available, resulting in lower recycling rates or lower-quality secondary feedstocks.
- Recycling companies are frequently unaware of or fail to leverage knowledge from other fields (e.g., AI, 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-scrap are not widely available, limiting these materials' recycling and recovery rates.

Appendix I

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