U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Sustainable Manufacturing Workshop

Workshop Summary Report

January 6-7, 2016

Portland, OR

The DOE Office of Energy Efficiency and Renewable Energy (EERE)'s Advanced Manufacturing Office partners with industry, small business, universities, and other stakeholders to identify and invest in emerging technologies with the potential to create high-quality domestic manufacturing jobs and enhance the global competitiveness of the United States.

This document was prepared for DOE/EERE's AMO as a collaborative effort between DOE AMO and Energetics Incorporated, Columbia, MD.

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1. Workshop Executive Summary

Executive Summary

The Department of Energy's (DOE) Office of Energy Efficiency & Renewable Energy (EERE)'s Advanced Manufacturing Office (AMO) held a workshop on Sustainable Manufacturing to gather input from stakeholders on future opportunities and technical challenges facing development and scale-up of transformative technologies, processes, and equipment for sustainable manufacturing. AMO also sought individual input on performance metrics and identification of key problem sets to be addressed. The intent was to define critical crosscutting barriers that, if successfully addressed, could enable step change impacts beyond the current state of the art. Technology development is expected to focus on the gap between lab-scale development and deployment and scale-up.

The workshop breakout groups identified the following key themes:

- **Developing and Using Alternative Feedstocks:** In order for industry to adopt alternative feedstocks, a positive cost-benefit ratio must be demonstrated, and the effects on industrial process performance and product qualification must be known and quantified. This will require process demonstration and validation at appropriate scales. More information and better quality data are needed to understand what waste streams exist, what their compositions are, and possible synergies among them. Improved (less energy-, materials-, and water-intensive) separations techniques are needed to make use of alternative feedstocks in a cost effective manner.
- **Reduction of Waste in Manufacturing Processes:** New technologies will be required to enhance "scrap" collection and separation to limit recycled feedstock contamination. Also, new manufacturing processes and technologies will be needed to cost efficiently re-engineer and recycle discarded finished products. This will help achieve goals such as reduction in water use by 20% by 2020, as well as the technology required to reduce cost of industrial water treatment by 50%. Material reuse was also discussed; a goal of increasing scrap metal reuse by factor of 2 by 2020 was suggested.
- **Sustainable Design and Decision-Making:** In design, end-of-life (EOL) considerations will need to become a primary driving force. Ease of reuse, recyclability, remanufacturing as well as sustainability of used materials need to be important factors that are taken into account early in the design phase. Better and integrated planning tools are needed to support sustainable design and decision-making. These tools will need to include all relevant externalities, not only economic and environmental factors.
- **End-of-Life Product Management:** EOL product management needs to focus on collection, recycling, upcycling, and remanufacturing. EOL management needs to be included as part of product design, with a goal to design products to achieve 100% disassembly. Upcycling can be increased by 20% with more efficient and effective waste recovery systems. A 50% or greater reduction in manufacturing waste to landfill by 2020 is a key objective.
- **Materials, Water and Energy Management:** There is a need to transition to more sustainable materials. A goal of 25% of renewable materials was suggested as a five-year goal. Even though many companies have focused on reducing energy use, significant room for improvement remains. For water consumption reduction, suggested targets varied from 10% in five years to the long-term goal of zero liquid discharge (ZLD) facilities and processes. To achieve very aggressive water reduction goals, such as ZLD, demonstration projects should be implemented in the most promising industries within five years.

During the five breakout sessions, a set of priority topics for research and development (R&D) emerged from discussions on the challenges and R&D needs identified for sustainable manufacturing, as shown in

Figure 1. These topics represent areas where a concerted R&D effort could help overcome major material and technology challenges. The topics are summarized below and described in more detail in Section 2 and Appendix E of this report.

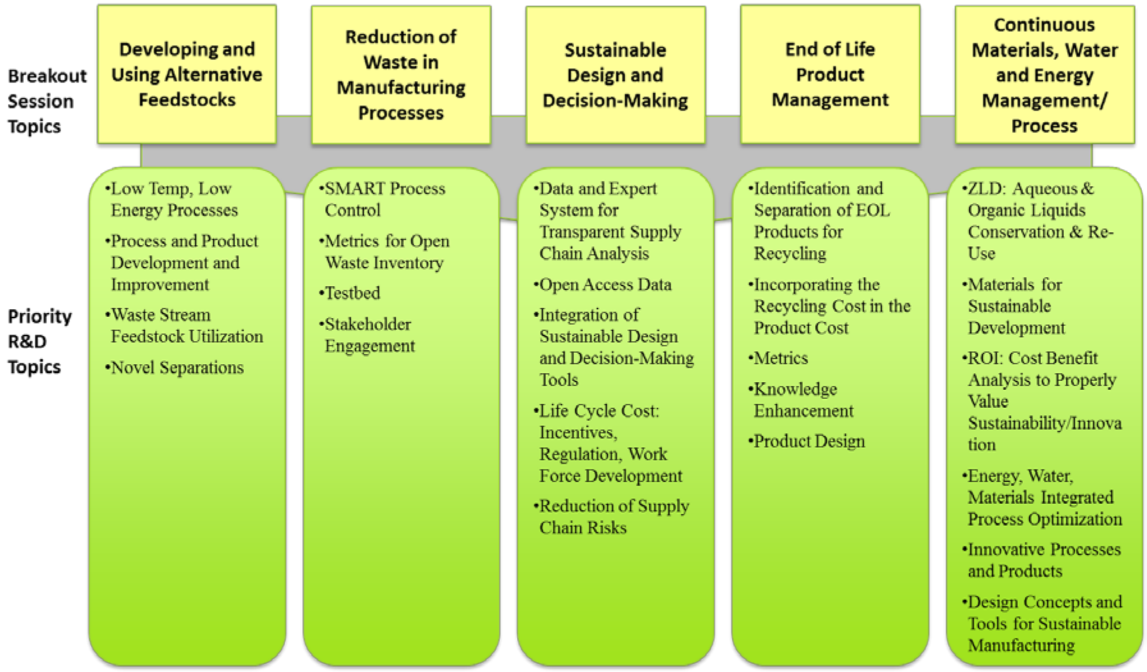

Figure 1. A set of priority R&D topics for Sustainable Manufacturing.

Description of the Opportunity

Sustainable manufacturing[1] encompasses a wide range of systems issues, including energy intensity, carbon intensity, and use intensity. Energy considerations alone are insufficient to capture the full range of impacts. A more complete understanding can be gained by tracking how materials flow through manufacturing supply chains and where resources such as materials, water, and energy are used throughout product life cycles. Increased material efficiency will reduce the material use intensity of supply chains, and in turn will provide additional opportunities for energy efficiency.

Between 1975 and 2000, per capita materials consumption in the United States grew an estimated 23% and total material consumption grew an estimated 57%[2]. By 2005, the U.S. used nearly 20% of the global primary energy supply and 15% of globally extracted materials, equivalent to 8.1 gigatons (GT). At

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[1] Numerous definitions for sustainable manufacturing are in use; all are concerned with the environmentally responsible production and use of manufactured goods. The U.S. Department of Commerce defines sustainable manufacturing as "the creation of manufactured products that use processes that are non-polluting, conserve energy and natural resources, and are economically sound and safe for employees, communities, and consumers." See http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp. The U.S. Environmental Protection Agency defines sustainable manufacturing as "the creation of manufactured products through economically-sound processes that minimize negative environmental impacts while conserving energy and natural resources." See http://www.epa.gov/sustainablemanufacturing/ glossary.htm. The Organisation for Economic Co-operation and Development defines it as "managing operations in an environmentally and socially responsible manner." See http://www.oecd.org/innovation/green/toolkit/aboutsustainablemanufacturingandthetoolkit.htm.

[2] WRI. 2008. Material Flows in the United States – a Physical Accounting of the U.S. Industrial Economy. World Resource Institute, Washington, DC. ISBN 978-1-56973-682-1. Available at: www.wri.org/sites/default/files/pdf/material_flows_in_the_united_states.pdf.

roughly 27 metric tons (MT) per person, U.S. per capita material use is higher than most high-income countries.[3] Global demand for engineering materials has increased by a factor of four over that last half century and is projected to continue to increase with the growing global population. On the output side, the U.S. generated close to 2.7 GT of waste in 2000. U.S. waste generation has increased 26% since 1975, with a 24% increase in harmful waste products (radioactive compounds, heavy metals and persistent organic chemicals).

Research and Development Needs

AMO's key interest in sustainable manufacturing is in technology development that improves energy efficiency and reduces greenhouse gas emissions while improving the efficiency of material use throughout the manufacturing process. Technology development could focus on: 1) testing and demonstration of alternative feedstocks; 2) reduction of waste throughout the manufacturing process; 3) testing and demonstration of specific technology to improve reuse and recycling of materials, water and energy within the manufacturing process and at the end of product life; and 4) validation and deployment of the tools, processes and technologies to enable sustainable design and assessment. If successfully developed, sustainable manufacturing tools and processes could serve as models and benchmarks for the broader manufacturing sector – enabling greater adoption of sustainability towards a goal of zero waste manufacturing, including materials, energy and water.

Workshop Overview

AMO partners with private and public stakeholders to improve U.S. competitiveness, save energy, create high-quality domestic manufacturing jobs, and ensure global leadership in advanced manufacturing and clean energy technologies. AMO invests in cost-shared research, development and demonstration (RD&D) of innovative, next generation manufacturing processes and production technologies that will improve efficiency and reduce emissions, reduce industrial waste, and reduce the manufactured product life-cycle energy consumption. AMO is particularly interested in advanced manufacturing technology challenges that might be overcome by pre-competitive collaborations conducted via a Manufacturing Innovation Institute (MII).

AMO held the Sustainable Manufacturing Workshop on January 6-7, 2016. Representatives from industry, academia, DOE national laboratories, and non-governmental organizations gathered in Portland, Oregon to hear keynote addresses and expert panel discussions, and to participate in workshop breakout sessions. Discussion topics focused on challenges and opportunities for new technology development that enables sustainable manufacturing, with a focus on improving energy-efficiency and reducing greenhouse gas emissions while improving the efficiency of material use throughout the manufacturing process.

Specific objectives include:

- Identify high value opportunities and manufacturing challenges to improve energy efficiency, reduce material/water use, and enable increased recycling and reuse.
- Discuss promising technologies and manufacturing systems that increase sustainability in manufacturing at the unit operations, facility, and system level.
- Strategize how best to leverage R&D among the public sector, industry, and academia.
- Encourage discussion and networking among leaders in the field.

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[3] Gierlinger, S., and Krausmann, F. 2012. The physical economy of the United States of America. Journal of Industrial Ecology. 16(3) 365-377.

Panel Discussions

A panel of subject matter experts (SME) provided their insights on the current progress, capability needs, and research trends on sustainable manufacturing. The panel was composed of experts from both academia and industry. Presentations given at the workshop are available at http://energy.gov/eere/downloads/workshop-sustainability-manufacturing-january-6-7. Biographies of the panelists can be found in Appendix D.

Highlights of the SME panel include:

- Ms. Jeanne Yu, the Director of Environmental Performance for Boeing Commercial Airplanes (BCA) at the Boeing Company, provided the industry's perspective for sustainable aviation. She highlighted to the audience that due to the increasing demand for aviation, greater emphasis on sustainability will be necessary. Also, sustainability is now viewed and measured from the economic, social, and environmental point of view, commonly referred to as the triple bottom line. She illustrated that, a decade or so ago, the Boeing Company was a novice when it came to sustainability, but has since then become a focal point for recycling aircrafts. She concluded her remarks with key technology challenges. For example, as the aerospace industry is moving toward composites, new cost effective approaches will be needed to recycle and/or reclaim these composites.
- Mr. Uli Schildt, an Energy Engineer at Darigold Incorporated, spoke about how DOE Better Plants program and Energy Star program helped Darigold become more sustainable. He encouraged the audience to view the Better Plants ISO 50001 standard as guideline that provides a firm a structured approach to achieve sustainability. Mr. Schildt believes that the industry has two key challenges ahead of it as it strives toward a more sustainable manufacturing. One is risk aversion; industry is very conservative, and therefore needs a lot of assistance to implement new technologies. Second is an aging workforce. For example, Mr. Schildt pointed out that the average age of the facility staff and mechanics that implement sustainable manufacturing technologies and practices at Darigold is over 50.
- Dr. I.S. Jawahir, Professor of Mechanical Engineering and James F. Hardymon Endowed Chair in Manufacturing Systems at the University of Kentucky, focused his discussion on the importance of a product life-cycle view on sustainability. To him, sustainable manufacturing cannot be viewed at the plant level. Instead, it is about creating a sustainable value chain where material can be reused. While the U.S. government, via the National Institute of Standards and Technology (NIST), has identified sustainability metrics for different life-cycle stages, progress is still slow in quantifying the systems and processes in terms of sustainability.
- Dr. Nabil Nasr, Associate Provost and Director of the Golisano Institute for Sustainability at the Rochester Institute of Technology, provided the attendees with his perspective on sustainable manufacturing. Dr. Nasr views sustainable manufacturing at the system level, beyond just the engineering and technical aspect of manufacturing. He informed the audience of the effort by the Organisation for Economic Co-operation and Development (OECD) to define sustainable manufacturing. OECD has identified 170 metrics to define and measure sustainable manufacturing, but concluded that these metrics have to be simplified to facilitate implementation. Dr. Nasr reflected on the necessity for companies to use the same language when discussing sustainable manufacturing, so that key challenges such as sustainable design, life-cycle engineering and sustainable supply chains, metrics/modeling, and remanufacturing processes can be addressed. There is a lot of interest around the world to understand the circular economy/material flow and what this means for sustainable manufacturing. More collaboration is needed to not only share ideas but also establish best practices.

Sustainable Manufacturing Technology Assessment

Mr. Joe Cresko, manager of Strategic Planning and Data Management at DOE EERE AMO, presented his efforts on the Technology Assessment (TA) – Sustainable Manufacturing/Flow of Materials Through Industry, developed as part of the Quadrennial Technology Review (QTR). While the QTR is a comprehensive assessment of science and energy technology R&D opportunities, this TA also examines the technical potential and enabling science of key sustainable manufacturing technologies.

In his talk, Mr. Cresko provided a framework to better capture the economy-wide effect of energy and GHG emissions, and to help characterize improvement opportunities, including:

- Changes in materials and industrial/manufacturing processes
- Material flows and manufactured products
- Cross-sector and life cycle impacts
- Embodied energy and GHGs

At the conclusion of the presentation, Mr. Cresko encouraged the workshop attendees to think about:

1. Innovative sustainable manufacturing technologies and system improvements that could yield the greatest economy-wide impacts
2. Methods and approaches to more sustainably leverage domestic energy resources
3. Types of investments that could enable U.S. leadership in different areas of sustainable manufacturing, such as
    - Developing and Using Alternative/Sustainable Feedstocks
    - Reduction of Waste in Manufacturing Processes
    - Sustainable Design and Decision-Making
    - End-of-Life Product Management
    - Materials, Water, and Energy Management

Workshop Discussions and Breakout Sessions

The workshop discussions provided AMO with further information on both cross-cutting and specific technology R&D challenges. The rationale for a MII, consistent with the mission of the DOE, was also discussed at the workshop. Five breakout sessions were conducted on the following topics:

- ***Developing and Using Alternative/Sustainable Feedstocks:*** What are the opportunities, challenges and barriers to develop alternative and more sustainable feedstocks, such as waste streams from other processes/industries? As an example, terpene (an organic waste product from the wood processing industry) has been explored both as a replacement for petroleum-based fuel and as potential feedstocks for the bulk and fine chemicals sector. What are the current barriers to wider implementation of such feedstocks? Other areas of interest include technology development needed to use renewable feedstocks as inputs to industrial processes, and the specific manufacturing needs for implementation of new feedstocks.
- ***Reduction of Waste in Manufacturing Processes:*** Within various industrial sectors, there are opportunities to improve material efficiency within manufacturing processes. As an example, inefficient material production and manufacturing processes produce in-plant scrap and represent opportunities to improve material use intensity. In the aluminum and steel industries, for example, in plant scrap is reusable and often contains fewer contaminants than post-consumer scrap. However, equipment for processing these materials may not be available, costs can be high, and many manufacturing facilities lack the infrastructure to reuse in-plant scrap. Beyond metals, opportunities for substantial waste reduction exist in many sectors. Potential topics of interest

include technology development that would reduce scrap/waste production, develop processes that reuse manufacturing wastes (e.g., depolymerization), and minimize material use within the manufacturing process.

- ***Sustainable Design and Decision-Making:*** For the private sector, it can be a challenge to properly calculate the benefit of investing in more sustainable technologies. Benefits of those investments do not always manifest as increased profit. Additionally, companies do not always bear the costs of unsustainable decisions. As an example, water discharged from a manufacturing facility may meet regulations, but the change in temperature or pH can still negatively impact the ecosystem. While certain companies have made sustainability part of their company values, others find it challenging to properly assess sustainability ("triple bottom line"). What are the barriers to improve sustainable decision-making? Design guidelines and tools are needed to facilitate sustainability accounting and decision-making, incorporating life-cycle analysis (including energy), materials minimization in manufacturing design and production, and design for disassembly.
- ***End-of-Life Management:*** Managing end-of-life (EOL) would ideally begin at the design stage to minimize waste and to increase reuse/recycling of materials. Current practices are varied across industrial sectors. In the certain sectors, EOL products are reused to a high degree. However, often that reuse is through down-cycling (i.e., recycling for use in a lower quality product or less demanding application). While down-cycling is preferable to landfilling or other disposal methods, development of new recycling technologies to retain the value of EOL materials is needed. Technologies that make product disassembly more efficient and improve reuse, recycling and remanufacturing are of interest. In addition to bulk single-material products, there are significant challenges in addressing reuse and recycling of multi-material products. As an example, there are EOL challenges with batteries used in electric and hybrid vehicles. As deployment of these batteries increases, technologies need to be developed to recover, reuse and recycle EOL materials.
- ***Materials, Water, and Energy Management:*** The concept of "reduce, reuse, and recycle" has been discussed for many years, with recycling at the forefront of related efforts. Reducing material use, however, has a large potential to reduce energy consumption early in the supply chain and in product manufacturing. Technologies that enable more efficient use of raw materials are of interest. For example, technologies that increase the useful lifespan of products through improved durability, and lighter weight materials are needed. Other areas for consideration include: supply chain and material sourcing; technologies to improve material efficiency within the manufacturing supply chain; reduction in bill of materials; and decentralized production of hazardous/toxic/harmful chemicals.

Participants in each breakout session answered a different set of questions that were appropriate for the topic. Summaries of the breakout group discussions and questions posed are outlined in the following chapters. The Appendices include the meeting Agenda (Appendix A), a combined list of participants from all the breakout groups (Appendix B), a list of acronyms (Appendix C), and full results of the breakout session discussions (Appendix E).

2. Summary of Results

Developing and Using Alternative Feedstocks

This session considered alternative feedstocks for sustainable manufacturing, which includes: (1) use of "waste products" generated in the manufacturing process (i.e., outputs not consumed in the final product or in its process of manufacture) as feedstock to produce energy or make another product; and (2) use of renewable (and/or less energy-, water-, or materials-intensive) feedstocks to produce energy or products. As an example, terpene (an organic waste product from the wood processing industry) has been explored both as a replacement for petroleum-based fuel and as a potential feedstock for the bulk and fine chemicals sector. The *Developing and Using Alternative Feedstocks* breakout group focused on three topics:

- Topic 1: Vision and Goals
- Topic 2: Challenges and Barriers
- Topic 3: R&D Needs and Priority R&D Topics

For each area, one focus question and several additional questions were posed. Individual participant's views and responses were captured using a compression planning and brainstorming process. Highlights of discussions are outlined below; the full results of discussions are provided in Appendix E.

Recurring Themes

Several themes emerged throughout the session, all of which are interconnected and contribute toward the vision of a cost-efficient use of alternative feedstocks. In order for industry to adopt alternative feedstocks, a positive cost-benefit ratio must be demonstrated, and the effects on industrial process performance and product qualification must be known and quantified. This will require process demonstration and validation at appropriate scales. More information (more and better quality data) is needed to understand what waste streams exist, what their compositions are, and possible synergies among them. Improved (less energy-, materials-, and water-intensive) separation techniques are needed to make use of alternative feedstocks in a cost effective manner. Lastly, basic and applied research is needed to develop better fundamental understanding of materials, process energetics, catalyst selectivity, atom-efficient conversion processes, and C1 chemistries.

Vision and Goals

The key themes identified during the discussion of vision and goals are highlighted below. The full results of the discussion are provided in Table A-1 of Appendix E.

- The highest-level "stretch" vision for developing and using alternative feedstocks is **zero-emissions industrial production**, in which all industrial inputs are used in final products or converted into value-added inputs for other industries or processes. Such systems would make full use of raw materials and maximize use of renewable and re-usable sources while minimizing pollution and eliminating waste.
    - Some industries could target zero emissions while others could target significantly reduced emissions. Specific reduction targets should be defined at an industry level.
- Goals would include:
    - Reduced greenhouse gas (GHG) emissions
    - Reduced water consumption
    - Reduced materials consumption
    - Cost-neutral to industry with demonstrated long-term viability of alternative feedstocks

Challenges and Barriers

The key themes identified during the discussion of challenges and barriers are highlighted below. The full results of the discussion are provided in Figure A-2 of Appendix E.

- **Feedstock Availability, Variability, and Characterization.** Lack of fundamental understanding of the availability and composition of potential alternative feedstocks is a major barrier to increasing their use in industrial processes. Different industries produce different waste streams, and have different input needs. Currently, there is not enough understanding of the various industrial input and output streams and possible synergies among them. The presence of undesirable contaminants in alternative feedstocks and the variability of feedstock composition is also a concern. For example, biomass-derived feedstock alternatives rarely have the purity and homogeneity that fossil fuel feedstocks offer, and purification processes can be expensive and energy-intensive. Better characterization of the composition and the range in composition of particular alternative feedstocks is needed. Another key challenge associated with alternative feedstocks is projecting the long-term availability of the feedstock, including the impacts of technology changes and business cycles over time that could make the feedstock itself obsolete.
- **Value Proposition.** Making changes to production processes can be both risky and costly, and businesses often do not know what effects a new feedstock will have on their process performance, product quality, or bottom line. Without a good understanding of the expected return-on-investment, companies will be unlikely to invest in changes required to utilize alternative feedstocks. The higher cost of using an alternative feedstock (whether real or perceived) is also a significant barrier.
- **Development Time.** The time it takes to develop and implement an alternative feedstock is a deterrent to innovation; current development timelines are too lengthy and can result in mismatches between technology readiness, product cycles, and feedstock availability. Development times (from concept to ready-for-pilot-scale-testing) should be reduced to no more than 2 years.

R&D Needs and Priority R&D Topics

The key themes identified during the discussion of R&D needs are highlighted below. The full results of the discussion are provided in Table A-3 of Appendix E.

- **Process Development and Improvement.** R&D is needed to improve current processes for utilizing alternative feedstocks. To address the challenge of variable feedstock composition, processes (or products) could be developed that take advantage of feedstock variability or find it to be irrelevant (e.g., polymers). Cost-effective feedstock preparation (materials handling, pretreatment, and breakdown) technologies are also needed to produce platform chemicals and building block products from alternative feedstocks. Simple techniques for utilizing alternative feedstocks available at low volumes are needed to take advantage of decentralized, lower-availability feedstocks that cannot capture economies of scale. Finally, **demonstrations** at pilot-scale are needed to validate technologies and demonstrate costs and benefits to industry.
- **Research to Build Fundamental Knowledge on "Green" Chemistry and Manufacturing Processes.** There are many opportunities for innovating current energy-, water-, and/or materials-intensive manufacturing processes. New scientific and engineering developments are needed to enable industries to minimize their environmental footprint while remaining profitable. For example, R&D into lower-temperature processes for cement and chemicals production could yield significant energy savings. More energy and cost efficient chemical separations techniques are also needed, including effective alternatives to aqueous separation processes, concentration techniques such as distillation, as well as improved catalysis and membrane separation processes.

Other R&D needs include fundamental understanding of process energetics (thermochemical and thermodynamic properties), atom-efficient conversion processes (through enhanced molecular reaction control), and development of C1 chemistries.

- **Data Compilation/Management and Analysis/Modeling.** Enhanced life cycle analysis tools are needed to accurately compare the costs and benefits of products generated through different processing routes and under different operating conditions through the full product life cycle. To effectively run and apply such analyses, improvements are needed in the quantity and quality of available data, as well as the approaches for evaluating life cycle metrics. This would include further characterization of available feedstocks and analysis of industrial process inputs/outputs and process integration opportunities.
- **Waste and By-Product Stream Utilization.** The effective utilization of waste streams (converting "wastes" to "feedstocks" or value-added inputs) is a key aspect of sustainable manufacturing. R&D needs identified in this area include lignin (and other bio-product) conversion and utilization, carbon dioxide capture and utilization, and consumer electronics recycling.

A set of priority topics for R&D emerged from discussions on the challenges and identified R&D needs for *Developing and Using Alternative Feedstocks*. These topics include areas where a concerted effort in R&D could help overcome major process and product development and technology challenges. For each priority R&D topic, the breakout session participants focused their discussion on the following:

- Key challenges
- Desired outcomes
- Appropriate near-term and the long-term R&D steps
- Performance goals and targets
- Potential participants and roles
- Impact on clean energy industry.

The topics are summarized below and described in more detail in Figures A-1 through A-4 in the Appendix.

- **Low-Temperature, Low-Energy Processes**: R&D to develop low-temperature, low-energy processes **for materials and chemical production** will enable simpler control of lower temperature/energy processes, lower capital and operating costs, and chemical/molecule/atom selectivity at lower temperatures. Two specific R&D activity areas were identified. First, targeted R&D to reduce the temperature of cement manufacture should aim to eliminate the kiln-based process and reduce the temperature of cement production to less than 600^{o}C. The second identified activity area was R&D targeted towards low-temperature hydrocarbon cracking, which could also have a goal for processing temperatures of 600^{o}C or less.
- **Process and Product Development and Improvement:** For this R&D topic area, two areas of activity were identified: (1) development of adaptive, robust industrial processing technologies that are scalable and flexible, so that factories and supply chains can more quickly (and at less cost) adapt to changing and variable feedstocks and (2) multi-functional products. These activities would enable factories that adjust to feedstocks as opposed to feedstocks that adjust to infrastructure, significantly reducing materials consumption, waste, and emissions.
- **Waste Stream Feedstock Utilization:** This R&D area addresses the need for new, economic technologies for processing industrial waste and byproducts. Targeted R&D to better characterize waste streams and develop and validate cost-effective, energy efficient processes for utilizing waste streams will result in economic benefits, including spin-off companies and job creation, and environmental benefits, including elimination of gas flaring and reduction in landfill waste.

- **Highly Efficient, Novel Separations:** Currently, a large fraction of industrial processing costs (both capital costs and operating costs) are spent on separation technologies, and many of these processes also suffer from inefficiency (loss of product) and unreliability (membrane fouling). R&D on highly efficient, cost-effective separation technologies would reduce industrial energy consumption, lower GHG emissions, increase product recovery efficiency, and reduce water utilization and consumption. Two specific areas of R&D activity were identified, including: (1) development of robust and selective membranes, and (2) process intensification to reduce or eliminate the need for separations.

Collaboration and Partnerships

In general, these activities are best suited for multi-partner (industry-national laboratory-university-government) partnerships. Multi-disciplinary collaboration is needed to investigate and solve the problems and develop analytical tools; R&D is needed at the basic, applied, and demonstration levels; industry input is needed at all stages of RD&D; and government support is needed for RD&D cost-sharing, standards development and product certification, and policy development (e.g., carbon and waste stream pricing). Particular roles for industry include supplying waste stream data and materials, vetting technical and economic assumptions, and helping to identify appropriate metrics. Workforce development is also important and should be part of the collaborative effort, especially at universities.

Reduction of Waste in Manufacturing Processes

The *Reduction of Waste in Manufacturing Processes* breakout group focused on three topics:

- Topic 1: Vision and Goals
- Topic 2: Challenges and Barriers
- Topic 3: R&D Needs and Priority R&D Topics

For each area, one focus question and several additional questions were posed. Individual participant's views and responses were captured using a compression planning and brainstorming process. Highlights of discussions are outlined below; the full results of discussions are provided in Appendix E.

Recurring Themes

Several themes emerged throughout the session, all of which are interconnected and contribute toward the vision of reducing waste. Participants discussed approaches to reduce water use by 20% by 2020, as well as the technology required to reduce cost of industrial water treatment by 50%. Material reuse was also discussed, with goals such as increase in scrap metal reuse by a factor of 2 by 2020. To achieve these goals, new technologies will be required to enhanced "scrap" collection and separation so as to limit contamination of recycled feedstock. Also, new manufacturing process and technologies will be needed to cost efficiently re-engineer and recycle spent products. Stakeholders will need to be educated so that there is a clear understanding of different sustainability processes and the benefits and ROI.

Vision and Goals

The key themes identified during the discussion of vision and goals are highlighted below. The full results of the discussion are provided in Table B-1 of Appendix E.

- **Water Resource:** One main goal is to reduce industrial water usage by 20% by 2020. Also, reduce the cost of industrial water treatment by 50%.
- **Reduce Scrap/Sub-par Parts:** Ideally, there will be new technologies and manufacturing processes that reduce scrap generation and increase reuse of scraps to achieve net-zero waste to landfill. This would be achieved by reducing in-plant scrap generation, increasing recyclability, and reducing off-spec product manufacturing (by 10% or more). Also, a proper business incentive will be needed, such as increasing the value of scrap/waste metal, so that the net cost of reducing scrap/waste metal is zero and/or the value of scrap/waste metal is doubled.
- **Design & Manufacturing Process:** Ideally, future products will be designed with reuse and recycling in mind; for example, design a product such that 50% of the content can be reused and 50% can be recycled. Manufacturing processes will need to be updated, so that energy intensity can be reduced by 25% in 10 years. For chemical processes, reduce the energy for separation from 22% of the overall energy use to 17% in 5 years. Heat recovery also needs to be increased, by as much as 20%.
- **Reuse:** One vision is to increase metallic scrap reuse two-fold by 2020. When discussing new materials such as carbon fiber, given that currently 30% of the carbon fiber is wasted as pre-press scrap, one vision is to turn carbon fiber pre-press scrap into semi-structural parts for aerospace or automotive industry.
- **Enterprise View:** One main goal is to develop an enterprise-wide strategy to implement sustainable technologies, including OEMs and their suppliers.

Challenges and Barriers

The key themes identified during the discussion of challenges and barriers are highlighted below. The full results of the discussion are provided in Table B-2 of Appendix E.

- **Process Understanding:** Understanding of some manufacturing processes is insufficient. A greater understanding is needed to develop approaches and methods to reduce waste.
- **Technology:** Currently, technology that makes it possible to re-engineer and cost efficiently recycle spent finished products is not available. There is only a limited availability of select sensors and smart process equipment that enables process control to enable waste reduction. Also, there is a lack of scrap separation technology to accommodate complex and varied alloys/materials. These complex materials must be separated during recycling before they can be reused.
- **Knowledge Gap:** Currently, there is minimum open knowledge of industry specific "waste" footprints that can be used to facilitate innovation and entrepreneurship. Also, publically available benchmarking data does not exist.
- **Test-Bed/Demonstration Facility:** Currently, there is a lack of test-beds and/or modular systems that enable testing and integration of emerging technologies at intermediate scale to demonstrate performance and cost as well as to lower deployment risks.
- **Stakeholder Buy-in:** One challenge is an insufficient understanding by manufacturers and consumers of the difference between up-front cost (profit) and life cycle cost. There is also a poor understanding of the economics of sustainable manufacturing. Specifically, stakeholders are unable to identify or discern processes that are profitable for industry.
- **Certification and Qualification:** The timeline to certify and qualify a new technology is too long.

R&D Needs and Priority R&D Topics

A set of priority topics for R&D emerged from discussions on the challenges and R&D needs identified for *Reduction of Waste in Manufacturing Processes*. These topics represent areas where a concerted effort in R&D could help overcome major sensor technology, algorithm, and process engineering/science challenges. For each priority R&D topic, the breakout session participants focused their discussion on the following:

- Key challenges
- Desired outcomes
- Appropriate near-term and the long-term R&D steps
- Performance goals and targets
- Potential participants and roles
- Impact on the clean energy industry.

The topics are summarized below and described in more detail in Figures B-1 through B-4 in Appendix E.

- **Smart Process Control:** This R&D topic focuses on developing process controls and technologies that enable more efficient use of raw material and further reduce scrap. Currently, there are few or no direct measurements of key manufacturing parameters available; sensor response times are too slow. When complete, there will be real-time measurements of complex processes and an ability to characterize complex, multi-variable processes.
- **Metrics for Waste Inventory:** This R&D topic will address the lack of metrics and measurement approaches for industry specific waste footprint. When completed, this will produce an industry

waste inventory, identify and aggregate best practices and improvement opportunities, and produce case studies on lessons learned and success stories.

- **Testbed:** This R&D topic will address the lack of intermediate performance data for promising low-TRL to mid-TRL technologies and limited industry funds for in-house pilot testing. Once this testbed effort is complete, industry will have an opportunity to de-risk new technology and understand its benefits. Performance data will also be available as a result of testing.
- **Stakeholder Engagement:** This R&D topic addresses the lack of incentives for industry to develop and study sustainable manufacturing. A desired outcome would include the launch of an institute for sustainable manufacturing. This institute would inform stakeholders about sustainable manufacturing processes, new technologies, and products. Business models would also be developed.

Collaboration and Partnership

The participants in this breakout session thought that an industry consortium is required to realize the vision of reducing waste in manufacturing processes. This would include multiple partners from industry, national laboratories, and academia. This consortium will facilitate collaborative R&D projects, including technology demonstration, and encourage broad collaboration. Focused R&D projects might require government funding to support development of methods, standards and case studies.

Sustainable Design and Decision-Making

This breakout group focused on three topics as they relate to *Sustainable Design and Decision-Making* in sustainable manufacturing:

- Topic 1: Vision and Goals
- Topic 2: Challenges and Barriers
- Topic 3: R&D Needs and Priority R&D Topics

For each topic area, a focus question was posed to the group with some additional clarifying guidance. Individual participant's views and responses were captured using a compression planning and brainstorming process. Highlights of discussions are outlined below; the full results of group discussions are provided in Appendix E.

Recurring Themes

Several themes emerged throughout the session, all of which are interconnected and contribute toward the vision of sustainable design and decision-making. The advancements are enabled by new analysis tools, databases, and business models. Key themes are:

- The need for more granular data and analysis tools was one of the most prominent themes in this group. Integrated planning tools are needed to support design and decision-making. Tools that convert data into actionable information and a database for relevant data are needed. IP restrictions and company preferences impact data availability, and even federally funded data are not always publicly available. Addressing the challenges related to the use of proprietary data is a high priority. Existing tools are not comprehensive enough to cover the full range of sustainability considerations. It is challenging to design tools that are broadly applicable.
- Related to tools and databases, the need for common metrics, models, and tools in areas such as risk and resiliency was identified. The tools need to produce actionable information and intelligence.
- Many discussions reiterated the need for open communication and accessible guidelines and resources. Deficiencies in communications within and across companies (supply chain) are a major obstacle to improved sustainability design and decision-making. Widely shared sustainability data, improved business models, incentives, supportive policies, and workforce education were suggestions for overcoming this.
- The need for developing business models conducive to comprehensive lifecycle considerations, and human resource changes was another recurring theme. Bringing this kind of true life cycle approach to design and manufacturing requires adequate communication within companies and the supply chain, as well as across industries.

Vision and Goals

The key themes identified during the discussion of vision and goals are highlighted below. The full results of the discussion are provided in Table C-1 of Appendix E.

- There is general agreement that better and **integrated planning tools** are needed to support sustainable design and decision-making. These tools will need to include all relevant externalities, not only economic and environmental factors. Developed tools should be flexible so that they can be utilized by different parts of a manufacturing organization and across disparate industries. There is also need to have tools that convert data into actionable information that is understandable to the public and decision makers.
- In design, **EOL considerations** will need to become a primary driving force. Ease of reuse, recyclability, remanufacturing, as well as sustainability of used materials need to be important

factors that are taken into account early in the design phase. In order to achieve this, relevant data, information, and tools will need to be available to manufacturers.

- **Achieving sustainability goals requires supportive policies, incentives, and programs**. An expanded DOE AMO Better Plants Program was identified as a potentially effective vehicle to support sustainability efforts in the manufacturing sector.

Challenges and Barriers

The key themes identified during the discussion of challenges and barriers are highlighted below. The full results of the discussion are provided in Table C-2 of Appendix E.

- Many of the major challenges and barriers identified are related to **lack of data and inadequate communication within organizations and across industries**. Availability of relevant data is limited due to IP restrictions and company preferences to not share information. Even data generated through federal funding is not always available publicly. Deficiencies in communication within companies and across industries—in particular companies designing products and those involved with EOL issues, such as recyclers—are a major obstacle. Information sharing within supply chains is also limited.
- Lack of **integrated design tools** is another major barrier. While there are tools available that cover economic and certain environmental aspects, they are not comprehensive enough to cover the full range of sustainability considerations regarding materials, products, and processes. Current design tools do not adequately address EOL qualities of products, such as reusability, ability to remanufacture, and recyclability. Significant variability between different industries makes it challenging to develop design tools that are broadly applicable.
- The dominance of short term thinking in industry management keeps it from considering the full lifecycle of products. **Current business models are not conducive to comprehensive lifecycle considerations**. There are also significant **human resource challenges** in implementing sustainable design in manufacturing. It is difficult to get all employees—from designers to factory floor workers—to think about sustainability and adjust their work accordingly.

R&D Needs and Priority R&D Topics

The key themes identified during the discussion of R&D needs are highlighted below. The full results of the discussion are provided in Table C-3 of Appendix E.

- There is a need to develop **new integrated design tools** for manufacturing industry that incorporate all relevant aspects of sustainability—including economic, environmental, and social factors. These **tools need to cover the whole lifecycle of a product, including EOL considerations**.
- In order to develop needed design tools and to support other decision making, **high-quality data on sustainability factors needs to be available and widely shared**. There is need to establish guidelines and mechanisms to provide researchers, companies, and other relevant stakeholders access to this data while taking into account IP restrictions and concerns. Open access and wiki models of sharing information should be pursued. Finding ways to share information across supply chains is a particular concern. The data also needs to be verified and validated.
- Addressing **lifecycle cost of new technologies and designs** is a priority. There is a need to educate the whole workforce, from upper management to factory floor, regarding the importance of considering the true lifecycle cost, including externalities. Providing financial relief from higher upfront cost through supportive policies and incentives should be a priority.

A set of priority topics for R&D emerged from discussions on the challenges and R&D needs identified for sustainable design and decision-making. These topics represent areas where a concerted effort in R&D could help overcome major material and manufacturing technology challenges. For each priority R&D topic, the breakout session participants focused their discussion on the following:

- Key challenges
- Desired outcomes
- Appropriate near-term and the long-term R&D steps
- Performance goals and targets
- Potential participants and roles
- Impact on clean energy industry.

The topics are summarized below and described in more detail in Figures C-1 through C-5 in the Appendix.

- **Data and Expert System for Transparent Supply Chain Analysis:** Research is needed in areas such as computational and software frameworks for data aggregation, increased use of sensors in manufacturing to gather granular data on processes, and expert systems to support decisions for sustainable manufacturing processes. This will enable the development of analysis systems that can better define and evaluate sustainable manufacturing across supply chain and entire life cycle of products.
- **Open Access Data:** There is a need to develop a database(s) that contain relevant sustainability data. In order to achieve this, appropriate models for gathering and sharing information must be developed, respecting company needs to safeguard intellectual property rights. Systems to validate and update data must also be developed. It is likely separate databases should be developed for manufacturing processes and materials.
- **Integration of Sustainable Design and Decision-Making Tools:** Existing tools need to be identified and their capabilities analyzed. Relevant metrics and indicators that are needed for tools and models must be identified. Sustainability assessment models required for the tools need to be developed, and those models need to be validated. These efforts will enable the development of design and decision-making tools that allow their users to properly take into account sustainability factors and constraints.
- **Life Cycle Cost – Incentives, Regulation, and Workforce Development:** For businesses to implement sustainable design practices and properly take into account true life cycle costs, incentives, supportive policies, and workforce education is needed. The R&D community can support such efforts by developing validated decision-making tools.
- **Reduction of Supply Chain Risks:** For suppliers, the ability to manage risk from new practices and designs is important to ensure that production and cost targets are achieved. To lessen these risks, there is a need to develop metrics for decision-making in areas such as risk and resiliency, as well as assessment tools for technology readiness.

Collaboration and Partnerships

Collaboration between private industry, academia, national laboratories, and other government agencies is essential to addressing identified barriers and achieving R&D goals. Collaboration and coordination of effort is of particular importance to sharing data that is needed for the development of needed models and tools. Within industry, engaging the whole supply chain and collaboration between different and disparate industries is needed, but difficult to achieve.

End-of-Life Product Management

The *End-of- Life Product Management* breakout group focused on three topics:

- Topic 1: Vision and Goals
- Topic 2: Challenges and Barriers
- Topic 3: R&D Needs and Priority R&D Topics

For each topic area, one focus question and several additional questions were posed. Individual participant's views and responses were captured using a compression planning and brainstorming process. Highlights of discussions are outlined below; the full results of discussions are provided in Appendix E.

Recurring Themes

Several themes emerged throughout the session, all of which are interconnected and contribute toward the vision of improving the EOL product management, with focus on collection, recycling, upcycling, and remanufacturing. Throughout the discussion, the participants recognized the importance of incorporating EOL management as part of product design, with a goal to design products to achieve 100% disassembly. However, in order to make a business case, the cost of EOL product management must be better understood, and perhaps incorporated into the product sales price to begin with. Stakeholders will need to develop a set of recycling metrics that indicate the environmental benefits of recycling different materials. New technology will also be required. For example, new technologies are needed to separate heterogeneous and multi-component materials.

Vision and Goals

The key themes identified during the discussion of vision and goals are highlighted below. The full results of the discussion are provided in Table D-1 of Appendix E.

- **Upcycling:** One vision is to increase upcycling by 20% with more efficient and effective waste recovery systems. The participants established a goal of 100% recovery by 2025 for critical materials. The participants also envisioned a mature infrastructure that encourages and increases recovery intensity.
- **Waste Reduction:** The participants envisioned a reduction of manufacturing waste to landfill by 50% or greater by 2020.
- **Strategic Guidance:** The participants established a vision of clear federal government leadership in procurement of sustainable chemical goods, with clear communication to the public by 2020. Also, it is envisioned that the communication and information sharing will improve between/among manufacturers and the various stakeholders in product end-of-use (e.g., recyclers, refurbishers, remanufacturers).
- **Design for EOL:** In the future, the goal is to design a product to achieve 100% disassembly and have an EOL plan, including elimination of solid waste disposal as an EOL option. One specific vision for the metal industry was focused on EOL management of coolants and lubricants, with a goal of extending functional life of industrial coolants/lubricants by 10x in 5 years; in 15 years, the goal will be to achieve 100% reuse via a closed system.
- **Collection:** One goal is to fully develop an efficient EOL collection system for North America, so that 100% of EOL products can be collected in a cost effective way.
- **Separation/Recovery Technology:** As many participants had a background in additive manufacturing and new materials such as carbon fiber, they envisioned a technology that melts down additive manufacturing parts and separate component metals/materials to 98% purity. Also,

they envision mature technology that enables 100% fiber recovery in a cost effective and environmentally sound manner.

Challenges and Barriers

The key themes identified during the discussion of challenges and barriers are highlighted below. The full results of the discussion are provided in Table D-2 of Appendix E.

- **Business Model:** One key challenge is that the cost of material does not represent the "total" cost of material, as recycling, upcycling, and recovery costs are not included. Also, the low cost of many raw materials prevents a paradigm shift from "how we have always done it" to an EOL paradigm.
- **Workforce:** There is a lack of training and educated workforce to execute the EOL product management work at all levels, from design to recycling.
- **Policy:** A key challenge is a highly fragmented EOL program and policy framework for consumers and industry to navigate, which adds costs to recyclers and other suppliers.
- **Lack of Incentive:** There is a lack of incentives and drivers for design for EOL. For example, consumers are not educated on the value of sustainability. A rational case has not been made for the value of EOL products.
- **Product Design:** One key challenge is that the current design process does not account for EOL product management. Design conflicts exist between what the consumer wants versus what facilitates EOL management. For example, consumer electronics are designed to be increasingly small, but not to be environmentally benign. Also, devices are becoming less modular and cannot be efficiently disassembled and separated.
- **Metrics:** A key challenge is a lack of methodology to quantify environmental or social costs and benefits. Improved metrics are needed to measure recycling efficiency.
- **Technology:** A key challenge is an immature material separation technology. For example, technology that effectively separate hybrid composites, mixed materials, and mixed metals does not exist. This is especially important in the context of additive manufacturing materials or composites. Also, current technology is insufficient in its ability to rapidly separate and identify materials.

R&D Needs and Priority R&D Topics

A set of priority topics for R&D emerged from discussions on the challenges and R&D needs identified for *End-of-Life Product Management*. These topics include areas where a concerted effort in R&D could help to overcome major process and equipment challenges. For each priority R&D topic, the breakout session participants focused their discussion on the following:

- Key challenges
- Desired outcomes
- Appropriate near-term and the long-term R&D steps
- Performance goals and targets
- Potential participants and roles
- Impact on the clean energy industry.

The topics are summarized below and described in more detail in Figures D-1 through D-5 in the Appendix.

- **Identification and Separation of EOL Products for Recycling:** Research is needed to address the challenges in product separation for recycling, especially when the feed mix is heterogeneous and contains multicomponent materials. An ability to identify and separate materials to meet stringent material specifications is required. New rapid and robust screening technologies and sorting systems need to be developed. These systems need to have low environmental impacts, energy use, and cost intensity.
- **Incorporating the Recycling Cost into the Product Cost:** This R&D topic addresses the lack of economy of scale that drives a net positive EOL value. Currently, virgin material is often artificially lower or similar in cost when compared to recycled materials. Also, there is no financial incentive for recycling such as tax breaks or penalties. In addition, local infrastructure for recycling/reuse does not exist. Businesses will need assistance in order to incorporate the real cost of materials into their product pricing, including EOL and environmental costs. Consumers will also need to be educated. A market driven by both consumers and industry is needed for EOL recycling.
- **Metrics:** There is a lack of metrics for EOL product management. Current mass-based recycling metrics do not measure environmental benefits for different materials. Also, the material loss in EOL processing is not measured. A simple and accepted set of metrics are needed to determine the environmental benefits for specific materials in a program that recycles products. Also, an accounting system is needed for tracking materials down the recycling chain on a material and product specific basis.
- **Knowledge Enhancement:** This R&D priority area addresses the lack of knowledge in the EOL product management community. The knowledge gaps include lack of awareness of product attributes by recyclers, lack of markets for material from end-of-use products, and lack of a forum for stakeholders to discuss EOL product design. Stakeholders need a forum to discuss EOL design and to improve the flow of information between stakeholders. The result will be a new market environment for material extracted from EOL products.
- **Product Design:** There is a lack of EOL practices in product design. Currently, metrics for evaluation of EOL design options do not exist. Integrated design tools are needed to address EOL options, and designers need sustainability evaluation information.

Collaboration and Partnership

The participants in this breakout session thought the required partnership is a multi-partner industry-university-national laboratory collaborative center. This collaboration is required to realize the vision of reducing waste in manufacturing processes. This collaborative will work with different levels of governments to drive the new U.S. program, serving as convener, technical expert, and administrator. This organization will interface with federal and state regulatory entities. This consortium will also facilitate collaborative R&D projects, including technology demonstrations, and encourage broad collaboration. Identification and development of key metrics will be another focus. Focused R&D projects might require government funding to support development of methods, standards and case studies.

Materials, Water, and Energy Management

This breakout group focused on three topics as they relate to *Materials, Water, and Energy Management* in sustainable manufacturing:

- Topic 1: Vision and Goals
- Topic 2: Challenges and Barriers
- Topic 3: R&D Needs and Priority R&D Topics

For each topic, a focus question was posed to the group with some additional clarifying guidance. Individual participant's views and responses were captured using a compression planning and brainstorming process. Highlights of discussions are outlined below; the full results of discussions are provided in Appendix E.

Recurring Themes

Several themes emerged throughout the session, all of which are interconnected and contribute toward the vision of a cost-efficient *Materials, Water, and Energy Management*.

- The need for **smart, practical, integrated, and economically viable technologies and processes** was evident throughout group discussions. Some technology areas discussed included reuse of polymeric materials, ZLD processes and water treatment solutions, integrated sensor networks, and custom material design. Also, **smart technology** is needed to enable the interoperability of industrial process systems and facilitate data collection and analysis. These technologies need to be priced so that smaller manufacturers can afford them, since much of U.S. manufacturing occurs in small companies.
- The need for more **granular data and analysis tools** was a recurring theme. The group emphasized the need to capture data from sustainable technology demonstrations, apply this to existing models, or develop new performance models, including cost benefit analysis. Developing and validating these granular models will enable creation of integrated software tools that capture production needs and externalities, and support product design for sustainability.
- Many discussions reiterated the need for **open and accessible guidelines and decision-making resources** for sustainable manufacturing. Optimization guidelines for volume minimization, access to demonstration results, and an available database of materials and properties were all suggestions for publicly available resources.
- As more interdependent systems are developed, they also become more complex. This makes managing the systems and processes more complex, and can also result in increased resource use. A common theme was the need for **broad-based collaboration and a systems focus**. This need for collaboration was also highlighted with respect to overcoming the divergence in motivation and decision-making across the supply chain and the need for new business models.
- Industry tends to be focused on **economic considerations** when it comes to resource use. Incentives and supportive policies are important to overcome high upfront cost and expected return on investment, but these solutions are largely outside of the R&D community and DOE's hands. Demonstrating drop-in technologies, proof of concept demonstrations, performance modeling, and validation are things that can be done to raise awareness of reduced capital expenditure and lessened payback time.
- Improved **process and product sensors and control systems** are essential enabling technologies for smart processes that will allow improved materials, water, and energy management in manufacturing.
- Improved understanding is needed of the **interconnections between materials, energy, and water use** over the entire product life cycle so that trade-offs can be properly understood and

accounted for in sustainable design and in assessing the value proposition for new technologies and processes.
- More **agile, flexible, and adaptable manufacturing processes** are needed, so products and processes can be relatively quickly and easily modified to meet sustainable design criteria.
- Sustainable manufacturing **design and modeling tools**, and the **databases** to support them, need to be developed and made available across the supply chain.

Vision and Goals

The key themes identified during the discussion of vision and goals are highlighted below. The full results of the discussion are provided in Table E-1 of Appendix E.

- **There is a need to transition to more sustainable materials.** A goal of 25% of renewable materials was suggested as a five-year goal. For polymeric materials, the goal should be to develop materials that can be used at least three times, processed in low temperatures, and with low water use. For reduction in the amount of landfilled materials by manufacturers, a target of 50% reduction in five years was suggested.
- **Even though many companies have focused on reducing energy use, significant room for improvement remains.** A goal of 75% reduction in non-renewable energy sources was suggested as a goal. This can be achieved through the use of efficient technologies, renewable energy, and smart product and process design. Energy management can also be improved through more efficient utilization of intermittent renewable resources and strategies such as peak shifting.
- For **water consumption reduction**, suggested targets varied from 10% in five years to long term goal of ZLD facilities and processes. To achieve very aggressive water reduction goals, such as ZLD, demonstration projects should be implemented in the most promising industries within five years. Chemical separation of metal ores was identified as one process that has the potential to achieve significant water reduction within the next 10 years.
- Develop technologies that reduce life cycle energy, water, materials and carbon intensity by an order of magnitude, leading to:
    - 1% or greater impact on U.S. energy consumption
    - Reduction of associated GHG emissions
    - Reduction of U.S. water consumption by 20%.

Challenges and Barriers

The key themes identified during the discussion of challenges and barriers are highlighted below. The full results of the discussion are provided in Table E-2 of Appendix E.

- Technology development is challenging due to a lack of deeper understanding of sustainability, interaction of relevant materials, and water-energy management. We are **lacking smart practical technologies that integrate optimal design, industry demands, and financial considerations**. A particularly pressing challenge is the lack of advanced technology for capturing granular data about energy, water, and materials used in manufacturing processes.
- There is a lack of understanding of how **materials, water, and energy are connected** over the manufacturing process and product life cycle. Making a change to improve one could have a negative impact on another, and often these connections, and their associated impacts, are not properly understood or valued. For example, reducing material intensity could decrease a product's lifetime, and recovering materials may be more energy-intensive than scrapping them.
- Design and decision making tools for sustainable manufacturing are needed, as is data to support these tools. Such tools are needed to help businesses recognize opportunities associated with

sustainable manufacturing and to help establish pricing and other incentives for optimizing efficiency and minimizing waste.

- Industry requirements regarding return on investment (ROI) and **preference for low upfront costs is a major challenge** for the deployment of more sustainable processes. Many technologies to reduce materials, energy, and water use are available. However, such technologies—especially those that result in significant reductions—often require too much capital and/or do not meet typical one or two year payback requirements.
- In the area of water management, **lack of ZLD processes and solutions** was identified as a major barrier. In particular, ZLD solutions are needed for fluids in distributed processes, such as cooling, cutting, and washing.
- An ineffective **materials development pipeline** is a challenge. The length of time it takes to develop new materials is one of the major problems. By the time new materials are developed, they are often obsolete for their intended purpose.
- The benefits and costs of sustainable investments are often **spread across the supply chain**. There is also a lack of visibility into the supply chain for decision making, which hampers the consideration of broader sustainability impacts.
- A fundamental factor that makes reduction of resource use—be it energy, water, or materials—more challenging is the **different motivations suppliers and end users** of these resources have. The supplier business model tends to be based on a desire to sell more, while end users want to use less. Much of the resource expertise resides with the suppliers, but it is usually not in their interest to reduce consumption.

R&D Needs and Priority R&D Topics

The key themes identified during the discussion of R&D needs are highlighted below. The full results of the discussion are provided in Table E-3 of Appendix E.

- There is a need to develop integrated, optimized technologies and processes that help achieve our sustainability goals. Such potential processes need to be identified, and they must be practical to implement and economically viable. To be able to develop these integrated solutions, one of the most significant needs is to develop **sensors and data analysis tools** to address the need **for more granular data** about industrial processes and their management. Data standards and analysis tools for "big data" are needed.
- **ZLD technology solutions** need to be developed for industries. Because of great variability between different industries and processes, no single solution can provide answers for all industries. New cost effective water treatment solutions are needed, such as membrane technologies. There is also a need to develop new alternative low-consumption solutions for processes where water is used as a coolant, including electrical generation applications.
- Typically, supportive policies and financial incentives are called for to address the challenge of inadequate return on investment that hampers the deployment of sustainable technologies. However, technical solutions are also needed to address this cost barrier. There is a need to develop better **early stage techno-economic models to evaluate potential new technologies** to ensure that the development of the most promising and viable technologies is being supported. In technology development, often the most viable solutions are "drop-in" technologies that utilize existing infrastructure and investments. There is also a need for better financial planning tools for the start-up phase of new technology development.
- A **more effective materials pipeline** needs to be developed. Many of the materials currently being used are not sustainable, so there is a need to develop new materials and models that enable the development of closed loop systems and processes. There is also a need to develop less expensive materials. As new materials are being developed, the needs of sustainable manufacturing must be a priority.

- **Process Innovation**. R&D is needed to develop modular, economically feasible, distributed manufacturing approaches for sustainable manufacturing. These technologies should provide manufacturers with more agility, flexibility, and adaptability so that products and processes can be relatively quickly and easily modified to meet sustainable design criteria. R&D is also needed to develop innovative material synthesis (and recovery) technologies that reduce water, energy, and waste simultaneously. To do this, more understanding about the interconnections between materials, energy, and water over the entire product life cycle will be required. Recovery and recycling of materials, especially in multi-material products, is often limited by economics; R&D is needed to develop cost effective recovery of spent multi-material finished products.
- **Product Innovation**. Product design and development tools and processes tend to focus on engineering specifications related to cost and performance of the product in use, with little, if any, priority given to the recyclability or reusability of the product, much less its sustainability impacts during use. Incorporating sustainability parameters into product design and manufacturing will require a paradigm shift, as well as new technologies and analytical tools. R&D needs include developing recycling friendly alloys (and other mixed materials like polymers, composites, etc.); sensors and automation to enable adaptive, reactive manufacturing processes; methods to better utilize post-consumer materials in new products; and "smart" products that provide feedback to sustainable design and manufacturing.
- **Sustainable Manufacturing Design Tools**. The development of integrated life cycle design tools with decision-support systems was identified as a major R&D need. These tools need to take upstream and downstream processes and choices into account, and be able to model materials, water, and energy use/trade-offs over the entire product life cycle using sustainability parameters. These tools need to account for and be deployed across the full manufacturing supply chain, and incorporate system level approaches that include industrial ecology.
- **Data and Analytics**. The ability to develop sustainable manufacturing design tools and innovate manufacturing processes and products will depend on the availability of appropriate data and analytics. This will require "big data" approaches to gathering, managing, accessing, analyzing, and interpreting data. Smart technology will be needed to gather data across the supply chain and enable interoperability and communication between key processes and systems. Databases are also needed on the material properties of secondary (post-consumer) materials, and industrial input and output streams. There is a need to address the paucity of data, as well as the disparity in the availability of data. While some firms have good tools for gathering and analyzing data, many others do not. Firms that do collect data are often reluctant to share the data for proprietary reasons.

A set of priority topics for R&D emerged from discussions on the challenges and R&D needs identified for materials, water, and energy management. These topics represent areas where a concerted effort in R&D could help overcome major materials, process, and technology challenges. For each priority R&D topic, the breakout session participants focused their discussion on the following:

- Key challenges
- Desired outcomes
- Appropriate near-term and the long-term R&D steps
- Performance goals and targets
- Potential participants and roles
- Impact on the clean energy industry.

The topics are summarized below and described in more detail in Figures E-1 through E-6 in the Appendix.

- **Aqueous and Organic Liquids Conservation and Re-Use:** New cost-effective treatment solutions need to be developed, including membrane, distillation, crystallization/evaporation, ion exchange, and chemical treatment technologies. Fluid and fluid process optimization guidelines for volume minimization need to be developed, and integrated demonstrations/pilot projects with well documented results should be conducted. The goal should be to reduce the cost of fluid use and disposal by 50%, as well as reduction of fluid input and disposal volumes by 50%.
- **Materials for Sustainable Development:** New materials and processes need to be developed with the goal of increasing reuse by 50% without adverse impact on the performance of the materials. An open and accessible database of sustainable materials and their properties needs to be established and maintained. The speed, effectiveness, and cost of material separation need to be improved. New technologies for evaluation and optimization of custom material designs are needed, as well as tools that support product design for recyclability and separation.
- **ROI – Cost Benefit Analysis to Properly Value Sustainability/Innovation:** "Drop-in" technologies that reduce capital expenditure and lessen payback time need to be demonstrated at bench scale. Data from the bench and pilot scale demonstrations needs to be gathered, and performance models need to be developed based on this data. Such models will enable down-selection of most promising technologies for further development. Cost benefit analysis needs to be linked with broader analysis that incorporates other sustainability factors.
- **Energy, Water, Materials Integrated Process Optimization:** New sustainable, integrated, and optimized manufacturing processes are needed. Process and sub-system level sensor networks to capture needed granular data should be developed. Gathered data needs to be applied to existing models, and these models validated. This will enable the development of integrated software tools that can capture full production costs and relevant externalities.
- **Innovative Processes and Products:** This R&D topic area is focused on developing technologies for integrated manufacturing ecosystems that achieve an order of magnitude reduction in water, energy, carbon, and/or materials use intensity and lead to a 1% or greater reduction in overall U.S. energy use. This includes the development of smart, interconnected technology for agile and flexible manufacturing systems and improved materials synthesis, recovery, and recycle/re-use technologies.
- **Design Concepts and Tools for Sustainable Manufacturing:** This R&D topic area targets the development of tools and data needed to understand and evaluate the interconnections and tradeoffs in materials, energy, and water use in manufacturing. The goal is the development of process and product design and decision support tools that meet sustainability goals while enabling industry to be profitable and create jobs. As a starting point, sustainable design concepts and models could be developed for a metals manufacturer, with the goal to demonstrate 10% reduction in water use, 50% in-plant recycling, and 30% longer product life.

Collaboration and Partnerships

The benefits of investing in sustainable manufacturing are often difficult to quantify because they are spread across the supply chain. The broad impacts dilute visibility. The group recognized this barrier and agreed that to achieve resource reduction goals, it is important to look at the issues as a system of processes. This involves collaboration between various suppliers, manufacturers, and other relevant stakeholders. Supply and demand integration is particularly challenging due to the differing motivations that suppliers and end users often have. To achieve this, new business models may need to be developed. Recent movement in this direction has been seen in the energy sector, as utilities are looking for new business models in the rapidly evolving environment caused by proliferation of cost-effective distributed energy options.

Appendix A: Agenda

Advanced Manufacturing Office
Sustainable Manufacturing Workshop
January 6-7, 2016

University Place Hotel & Conference Center
310 SW Lincoln St
Portland, OR
866-845-4647

Final Agenda

Day 1 (January 6)	
8:00 – 8:30 am	REGISTRATION FOR ATTENDEES
8:30 – 8:40 am	Welcome **Mark Johnson**, Director, DOE Advanced Manufacturing Office
8:40 – 8:50 am	DOE Remarks **Mark Johnson**, Director, DOE Advanced Manufacturing Office
8:50 – 9:20 am	Advanced Manufacturing Office: Introduction and Interest in Sustainable Manufacturing **Mark Johnson**, Director, DOE Advanced Manufacturing Office
9:20 – 10:20 am	Panel Discussion on Sustainable Manufacturing **Invited Participants** • Jeanne Yu, Boeing • Uli Schildt, Darigold • I.S. Jawahir, University of Kentucky • Nabil Nasr, Rochester Institute of Technology
10:20 – 10:50 am	Sustainable Manufacturing Technology Assessment **Joe Cresko,** DOE Advanced Manufacturing Office
10:50 – 11:00 am	Breakout Session Instructions
11:00 – 11:20 am	BREAK
11:20 am – 12:20 pm	Breakout Sessions: ➢ Developing and Using Alternative Feedstocks ➢ Reduction of Waste in Manufacturing Processes ➢ Sustainable Design and Decision-Making
12:20 – 1:20 pm	LUNCH
1:20 – 4:00 pm	Breakout Sessions (Continued): ➢ Developing and Using Alternative Feedstocks ➢ Reduction of Waste in Manufacturing Processes ➢ Sustainable Design and Decision-Making

4:00 – 4:30 pm	BREAK
4:30 – 5:00 pm	Breakout Session Summaries
5:00 pm	Adjourn

Day 2 (January 7)	
8:00 – 8:30 am	REGISTRATION FOR ATTENDEES
8:30 – 9:00 am	Facility Public-Private Partnerships in AMO **Mark Shuart**, DOE Advanced Manufacturing Office
9:00 – 9:10 am	Breakout Session Instructions
9:10 am – 10:30 am	Breakout Sessions: ➢ End-of-Life Product Management ➢ Materials, Water and Energy Management
10:30- 11:00 am	BREAK
11:00 am – 12:15 pm	Breakout Sessions (Continued): ➢ End-of-Life Product Management ➢ Materials, Water and Energy Management
12:15 – 1:15 pm	LUNCH
1:15 – 2:45 pm	Breakout Sessions (Continued): ➢ End-of-Life Product Management ➢ Materials, Water and Energy Management
2:45 – 3:00 pm	BREAK
3:00 – 3:30 pm	Breakout Session Summaries
3:30 – 4:00 pm	Closing Comments **Mark Johnson and Mark Shuart**, DOE Advanced Manufacturing Office
4:00 pm	Adjourn

Appendix B: Workshop Participants

Name	Organization
Bryant Bainbridge	Specialized Bicycles
Balu Balachandran	Argonne National Laboratory
Robert Baldwin	National Renewable Energy Laboratory
Frank Blum	Oklahoma State University
Mark Caffarey	Umicore USA
Alberta Carpenter	National Renewable Energy Laboratory
Matthew Carter	The Boeing Company
John Collins	Idaho National Laboratory
Claudio Corgnale	Savannah River National Lab / Savannah River Consulting
James Cornwell	Universal Recycling Technologies
Daniel Coughlin	American Composites Manufacturing Association
Jeffrey Cramer	38 North Solutions
Joe Cresko	U.S. Department of Energy – Advanced Manufacturing Office
Edward Daniels	Argonne National Laboratory
Richard Donovan	University of California, Irvine
Corinne Drennan	Pacific Northwest National Laboratory
Bryony DuPont	Oregon State University
Jonathan Fink	Portland State University
Kendra Flagged	Self
Kevin Gardner	University of New Hamsphire
William Gerry	The Boeing Company
Daniel Ginosar	Idaho National Laboratory
Alison Gotkin	United Technologies Research Center
Karl Haapala	Oregon State University
Sandie Hallman	The Boeing Company
Carol Handwerker	Purdue University
Tim Hansen	Southern Research
David Hardy	U.S. Department of Energy – Advanced Manufacturing Office
Stewart P. Harrison	Advanced Recovery, Inc.
Michael Haselkorn	Rochester Institute of Technology
Michael Heitkamp	Savannah River National Laboratory
Yinlun Huang	Wayne State University
Robert Hyers	Boston Electromet
I.S. Jawahir	University of Kentucky
Cynthia Jenks	Ames Laboratory
Ed Jones	Lawrence Livermore National Laboratory
Joseph Junker	Oregon State University Energy Efficiency Center (a U.S. DOE Industrial Assessment Center)
Alex King	Critical Materials Institute
Daniel Kopp	Rutgers, The State University of New Jersey
Eli Levine	U.S. Department of Energy – Clean Energy Manufacturing Initiative
GuannPyng (G.P.) Li	University of California, Irvine
Tedd Lister	Idaho National laboratory
Thomas Lograsso	Ames Laboratory
Jennifer Mangold	University of California, Berkeley

Name	Organization
Mike McKittrick	U.S. Department of Energy – Advanced Manufacturing Office
Robin Miles	Lawrence Livermore National Laboratory
Nabil Nasr	Rochester Institute of Technology
Michael Ohadi	University of Maryland
William (Bill) Peter	Oak Ridge National Laboratory
Eric Peterson	Idaho National Laboratory
Coleen Pugh	The University of Akron
Behnaz Rezaie	University of Idaho
Uli Schildt	Darigold Incorporated
Steve Shade	Purdue University
Mark Shuart	U.S. Department of Energy – Advanced Manufacturing Office
Mark Soucek	University of Akron
Vicki Thompson	Idaho National Laboratory
Michael Thurston	Rochester Institute of Technology
Mayank Tyagi	Louisiana State University
David Wagger	Institute of Scrap Recycling Industries
Jason Wible	U.S. Department of Energy – ARPA-e
Aaron Wilson	Idaho National Laboratory
Mark Wright	Iowa State University
Vikram Yadama	Washington State University
Jeanne Yu	Boeing Commercial Airplanes
Fu Zhao	Purdue University

Appendix C: Acronym List

AMO	Advanced Manufacturing Office
ASTM	ASTM, formerly referred to as the American Society for Testing and Materials
BIPV	Building-integrated photovoltaics
CAPEX	Capital expenditure
CRADA	Cooperative Research and Development Agreement
DFT	Density functional theory
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EERE	Office of Energy Efficiency and Renewable Energy
EOL	End-of-Life
EOS	End of service
FAA	Federal Aviation Administration
FDA	U.S. Food and Drug Administration
FOA	Funding Opportunity Announcement
GT	Gigaton
IP	Intellectual property
kWh	Kilo Watt hours
LBS	Pounds
LCA	Life Cycle Analysis
Mph	Miles per hour
MRL	Manufacturing readiness level
MT	Metricton
MWH	Megawatt Hours
NDE	Non-destructive Evaluation
NDT	Non-destructive Testing
NEC	National Electrical Code
NIST	National Institute of Standards and Technology
NNMI	National Network for Manufacturing Innovation
NSF	National Science Foundation
O&M	Operating and maintenance
OCED	Organisation for Economic Co-operation and Development
OEM	Original Equipment Manufacturer
OLED	Organic light emitting diodes
OPEX	Operating expense
ORNL	Oak Ridge National Laboratory
QA	Quality assurance
QC	Quality control
Quads	Quadrillion British thermal units (quads)
QTR	Quadrennial Technology Review
PV	Photovoltaics
R&D	Research and development

RD&D	Research, development and demonstration
RFI	Request for Information
ROI	Return on investment
SBIR	Small Business Innovation Research
SPD	Suspended particle devices
SME	Subject matter expert
SPP	Strategic Partnership Project
SS	Stainless steel
TA	Technology Assessment
TRL	Technology readiness level
ZLD	Zero Liquid Discharge

Appendix D: Panelist Biographies

Ms. Jeanne Yu, Director of Environmental Performance, The Boeing Company

Ms. Jeanne Yu is the Director of Environmental Performance for Boeing Commercial Airplanes (BCA) at the Boeing Company. She has responsibility for developing Environmental Performance strategy and ensuring current and future BCA products are environmentally progressive. She leads the team responsible for the innovative ecoDemonstrator Program, a flight test program to accelerate technology implementation. She was one of the key industry leaders at Boeing responsible for establishing the viability of sustainable Biofuel for use in commercial aircraft and in partnering with airlines to conduct flight tests with Biofuel blends. She received a Bachelor of Science degree in Mechanical Engineering from the University of Illinois in 1984 and holds a Master of Science in Mechanical Engineering-Thermo Sciences from Stanford University. She has also been featured in Changing Our World: True Stories of Women Engineers.

Mr. Uli Schildt, Energy Engineer, Darigold Incorporated

Mr. Uli Schildt is an Energy Engineer at Darigold Incorporated, a farmer-owned milk products manufacturing company representing over 500 family farms throughout the Northwest. Darigold's processing plants produce milk, butter, sour cream, cottage cheese, and other dairy products. Mr. Schildt has been involved in Energy Management for over 10 years. He has implemented Energy Management Programs with two different companies and was a participant in the Department of Energy ISO 50001/SEP Northwest Energy Management Demonstration Pilot. He is a Certified Energy Manager, Certified Energy Auditor, Certified Practitioner in Energy Management Systems, Certified ISO 50001 Auditor, and DOE AIRMaster+ Specialist.

Dr. I. S. Jawahir, Professor of Mechanical Engineering, University of Kentucky

Dr. I.S. Jawahir is a Professor of Mechanical Engineering and James F. Hardymon Endowed Chair in Manufacturing Systems at the University of Kentucky. His current research interests are in the areas of sustainable manufacturing, focusing on predictive performance models for products, processes and systems. He is the Founding Director of the Institute for Sustainable Manufacturing (ISM), a multidisciplinary collaborative unit whose primary objectives are to develop and advance sustainable manufacturing principles and practices. Professor Jawahir is a well-accomplished, internationally recognized researcher and educator. He has produced over 350 technical research papers, including 140 refereed journal papers, and has been awarded with 4 U.S. patents. He has delivered 46 keynote papers in international conferences and over 150 invited presentations in 32 countries. He is a fellow of International Academy for Production Engineering, American Society of Mechanical Engineers, and Society of Manufacturing Engineers. In June 2013, Professor Jawahir received the 2013 ASME Milton C. Shaw Manufacturing Research Medal for his outstanding research contributions. More recently, in December 2015, he was awarded the 2015 William Johnson International Gold Medal for his lifetime achievements in academic research and teaching in material processing at the 2015 Advances in Materials and Processing Technologies (AMPT) Annual Conference held in Madrid, Spain.

Dr. Nabil Nasr, Associate Provost and Director of the Golisano Institute for Sustainability, Rochester Institute of Technology

Dr. Nabil Nasr is the Associate Provost and Director of the Golisano Institute for Sustainability at RIT. In 1997, he founded the Center for Remanufacturing and Resource Recovery, which has become a leading source of applied research and solutions in remanufacturing technologies. Since 2002, he has served as Associate Provost and Director of the Center for Integrated Manufacturing Studies, whose mission is to increase competitiveness of manufacturers through technology development and transfer. In 2007, he became the founding director of the newly established Golisano Institute for Sustainability with a focus on sustainable production systems and the built environment. For over 25 years, Dr. Nasr has worked in the fields of sustainable manufacturing, remanufacturing, cleaner production, and sustainable product development and is considered an international leader in R&D efforts in these disciplines. He has served as an expert delegate for the U.S. government in several international forums, including the Asia Pacific Economic Cooperation (APEC), the United Nations, and the World Trade Organization. He is a member of the United Nations Environment Program's (UNEP) International Resource Panel (IRP). He also served as chair of the OECD Advisory Expert Group on Sustainable Production and Eco-Innovation from 2008-2011 and the National Research Council (NRC), National Materials and Manufacturing Board (NMMB) 2011-2013.

Appendix E. Detailed Breakout Results

A. Developing and Using Alternative Feedstocks

Vision and Goals

FOCUS QUESTION 1: *In the next five years, what goals would we like to achieve for the development and use of alternative feedstocks? What are some of the specific targets we would like to reach?*

Table A-1 summarizes participant comments on the Vision and Goals they would like to strive toward in the development and use of alternative feedstocks.

Table A-1. Vision and Goals
Scope

• Alternative feedstocks for sustainable manufacturing
    • Use of current waste products in the manufacturing process as feedstock (for energy generation or to make another product)
    • Use of renewable feedstocks to produce energy or products

Vision

• Zero-emissions industry
    • Especially energy intensive industries like cement, refining, steel, and chemicals
• Make manufacturing more energy and resource efficient
    • Reduce greenhouse gas (GHG) emissions
    • Reduce materials consumption
    • Metrics (percent reduction targets) will vary by industry

Targets and Metrics

• Reduce time required to develop alternative feedstock (concept to pilot scale) to 2 years
• Develop better understanding of what feedstocks are "ripe" for alternatives
• Make cross-cutting platforms for using products (e.g., sugars, CO_2, lignin)
    • Platforms that make use of existing infrastructure
    • New platforms that are robust and adaptable to changing feedstocks
• Develop a feedstock with a positive cost-benefit ratio that manufacturers can (and will) use
    • Must meet process specifications
    • Must pass product qualifications
• Analysis that shows that the current state-of-the-art for manufacturing is not viable (i.e., not sustainable over the long term). Need analysis that shows what happens under a "business as usual" scenario.
    • Quantify impacts
    • What is the cost?
    • Effect on business and revenues (sustainable = businesses can keep making money)
• De-risk the use of the feedstock (and make it cost less!)
• Demonstrate long term viability of the feedstock (100 years)

Challenges and Barriers

FOCUS QUESTION 2: *What are the key challenges/barriers to the development and use of alternative feedstocks? What are the problems we are trying to solve?*

Table A-2 summarizes participant comments on challenges and barriers to development and use of alternative feedstocks. Workshop participants were asked to vote on the challenges and barriers they perceived as most important. The number of votes received (indicating participants' highest priorities) is shown by asterisks and the vote count is in parentheses.

Table A-2. Challenges and Barriers
Feedstock Availability and Cost

• Availability of feedstock and changing technology may make the feedstock obsolete *******(7)
  • e.g., cathode-ray tubes
• Feedstock cost (free is good but low cost is okay) ****(4)
  • Prices are low until a market appears
• No alternative supply available **(2)
• Lack of long term guarantees of feedstock costs availability **(2)
• Lack of feedstock logistics knowledge
• Lack of infrastructure

Feedstock Variability
• Alternative feedstocks are highly variable (amount/availability and composition) and non-homogeneous *********(9) • Lower quality of alternative feedstocks *(1) • Undesirable contaminants • Lack of feedstock characterization that matches industry needs
Fundamental Knowledge
• Lack of fundamental research that would enable development and utilization of new feedstocks ***(3) • Inability to reuse mixed/hybrid materials
Institutional Barriers
• Lack of ability to demonstrate process at intermediate level (pilot scale) ****(4) • Consumer preferences (behavioral economics) *(1) • Economic "leakage" • Lack of capital (cleantech investment)
Analytical Gaps
• Inability to perform accurate life cycle analysis *(1) • Current life cycle analysis (LCA) methodologies reward inefficiencies (e.g., reducing heat loss in power generation is equivalent to displacing coal use, a huge LCA gain)
Acceptance by Manufacturer
• Infrastructure lock-in **(2) • Inability to utilize (and amortize) existing plant *(1)   • Too many (or too complex) changes needed so industry is not interested • Impact on "other" resources is uncertain (water, new waste streams) *(1) • Inability to process economically • Lack of standards and certifications • Lack of agility in the existing manufacturing infrastructure to adjust to change/risk
Value Proposition

Table A-2. Challenges and Barriers
• Lack of a rapid cash-flow opportunity (excessive complexity and interdependence) ******(6) • Failure to deliver technologies at appropriate times in the business cycle ****(4) • Not in core business plan • Feedstock supplies that don't readily meet needs of industry • "Value" for industry is not understood

R&D Needs

FOCUS QUESTION 3: *Drawing on the technical challenges identified, what critical R&D is needed to overcome the major challenges, address scalability, and advance new technologies in sustainable manufacturing in regards to alternative feedstocks?*

Table A-3 summarizes participant discussions on the critical technology R&D that will be required to increase the development and use of alternative feedstocks for sustainable manufacturing. Workshop participants were asked to vote on the R&D needs they perceived as most important. The number of votes received (indicating participants' highest priorities) is shown by asterisks and the vote count is in parentheses. In the following pages, Figures A-1 through A-4 present an analysis of the highest priority R&D topics for *Developing and Using Alternative Feedstocks*.

Table A-3. R&D Needs

Process Development and Improvement

- Pilot scale demonstrations ******(6)
    - Detailed validation
    - Understand coupling
- Feedstock preparation to reduce variability *****(5)
- Cost-effective biomass (including algae) deconstruction technologies ****(4)
- R&D technologies that escape economies of scale, and are simple. This aims toward addressing decentralized, lower-availability feedstocks, and highly variable feedstocks *(1)
- R&D to lower the cost and increase availability of micro-organisms for fermentation *(1)
- R&D to develop cost effective conversion technologies to high value intermediate *(1)
- Better understanding of feedstock constituent toxicity/toxicology
- Matching products to feedstock, e.g., industrial oxygenates
- Cost decrease for enabling technology

Product Development

- Develop products/processes that take advantage of feedstock variability or find it to be irrelevant **(2)
- Co-product development to improve process economics

Analysis (Chemical and Process)

- Characterization of feedstocks (maybe with standards) ***(3)
- Examine technology or process synergies and integration opportunities *(1)
- Develop accurate metrics for life cycle analysis
- Industry feedstock characterization (focused on improving process flexibility)

Basic (Cross-cutting) Research

- Lower temperature, lower energy intensity processes **********(10)
- Novel chemical separations techniques *******(7)
    - Low-cost, highly efficient
- Catalysis/kinetics (highly selective catalyst development) ********(8)
- Develop C-1 chemistry *****(5)
- Understand process energetics (thermochemical and thermodynamic properties) ***(3)
- Atom efficient conversion processes **(2)
- Investment into fundamental research *(1)
- Numerical modelling and experimental confirmation
- Develop processing technologies to produce high quality alternative feedstocks
- R&D on feedstock processing

Table A-3. R&D Needs
Waste Stream Utilization
• Lignin conversion and utilization ****(4) • Develop efficient technologies to convert CO_2 into useful/value-added products or process inputs *****(5) • Develop efficient and inexpensive CO_2 capture and release technologies **(2) • Modular natural gas processing **(2) • Consumer device recycling *(1)
Economics
• Economic forecasting/modeling *(1) • Improved techniques for bringing feedstocks to manufacturer (logistics) • Supply chain analysis
Crosscutting
• Reduction in water use ***(3) • Analysis of “lessons learned”

Figure A-1. Low Temp, Low Energy Processes

KEY CHALLENGES:	DESIRED OUTCOMES:
• Many processes developed for high energy/temperature conditions • Energy conservation not adequately taken into account • Kinetics is a challenge • Yield efficiency and selectivity	• Simpler control of lower temperature, lower energy processes • Lower capital costs • Lower energy costs • Selectivity at lower temperatures is possible • Lower operating costs

	Low Temperature/Energy Production of Materials	Low Temperature/Energy Chemical Production
R&D Approach		
<3 years	• Evaluate mechanisms for temperature reduction for cement manufacture	• Reduce energy consumption for polymers for emerging technologies • Reduce cracking temperatures for hydrocarbons on bench top
>3-5 years	• Reduce processing temperatures for cement manufacture • Eliminate kiln process	• Scale up to production for specific technologies • Extend approaches to existing high volume polymer technologies • Develop pilot level processes for lower cracking temperature hydrocarbons
Performance Goals and Targets		
Metrics	• Reduce cement production to 600 degrees C and lower energy	• Reducing cracking temperatures below 600 degrees C

Potential Participants and Roles

Stakeholders

Industry/Users: Set parameters for proposed reductions
Industry/Material:
National Labs: contribute to design needs, validations, characterizations, and super computing resources
Academia: workforce development, fundamental research
Associations: standards development

Impacts

Saves energy: high - serious reduction in energy for high volume materials
Reduces carbon, wastes, emissions, water: medium - savings from energy reductions
Accelerates innovation: medium - large impact on high volume production but not necessarily generalizable
Reduces costs: medium - primarily energy costs
Improves product quality: medium - may lead to different chemical species/phases produced
Improves competitiveness: medium
Increases raw material efficiency / yields: high - better utilization of feedstocks

Figure A-2. Process and Product Development and Improvement

KEY CHALLENGES:	DESIRED OUTCOMES:
• Flexible, adaptive, scalable technologies don't exist • Process improvements need to meet commercial inertia without interrupting entire supply chains (e.g., translate across supply chains) • Specifications for new products requires generation of significant quantities of product (e.g., 1-2 liters) early in project development, while most labs work at milligram scales • Feedstock variability, availability, deliverability	• Scalable, adaptive technologies • Technology development that matches commercial/consumer inertia • Process development driven by improvements in efficiencies (vs cost drivers) • Revolution in capital equipment (a re-imagined factory) • "Smart" manufacturing ("internet of things")

	Adaptive, Robust Technologies	Multi-Functional Products
R&D Approach		
<3 years	• Process control/automation technologies • Engineering relevant data and strategic analysis • Catalysis development	• Atom-efficient process development • Multi-scale modeling or understanding of materials and materials interactions • Process development that does not require elimination of hetero atoms • LCA and accelerated aging of products testing to control EOL
>3-5 years	• Predictive models • Optimization of process design	• Optimization of product design • Field testing by multiple users
Performance Goals and Targets		
Metrics	• Factories that adjust to feedstocks vs feedstocks that adjust to infrastructure • Net zero supply chain (circular economy concept) • 60% GHG reduction • 85% recyclability of materials of construction	• Performance that meets or exceeds metrics achieved by incumbent product • New markets for new (or known) materials manufactured via new processes
Potential Participants and Roles		
Stakeholders	Industry/Users: materials production and testing industrial advisory role Industry/Material: innovations ecosystems (spin offs) National Labs: basic and applied R&D, technology transfer, materials production Academia: basic R&D, workforce training, technology transfer Associations: consortia, working groups Other: Non-DOE agencies: these support product testing and standards development	

Impacts

Saves energy: high - Energy efficiencies lead to large gains
Reduces carbon, wastes, emissions, water: high - Circular economy, or bio/waste based
Accelerates innovation: high - Re-imagined factories and product replacement within 2 years
Reduces costs: medium - Waste utilization can lower feedstock cost
Improves product quality: medium - Recyclable products
Improves competitiveness: high - New markets
Increases raw material efficiency / yields: high - Multi-functional products

Figure A-3. Waste Stream Feedstock Utilization

KEY CHALLENGES:	DESIRED OUTCOMES:
• Variability of waste streams • Working with and separating contaminants • Scale and location • Scale up (economics) • Pricing of waste streams (externality) • Pre-processing of feedstock	• Economical process/product • Waste minimization • Economic model-waste stream feedstock logistic models • Robust production process; segmentation process • New vs old: job creation

	Variables of Waste Stream	Waste Stream to Feedstock
R&D Approach		
<3 years	• Bench-scale mechanical and chemical processes • Characterization of waste streams—development, identification of major or similar components • Processing modeling/model validation • Economic modeling/validation	• Bench-scale (5 gal)/process demonstration (25 gal) • Micro-organism development, biological conversion (understanding genetics) • Economic/process modeling • Understanding feedstock scale and location for economic and process models
>3-5 years	• Process demonstrations • Development of methods for separating components	• Pilot demonstration • Micro-organism production—large quantities • Multiple processes demonstrative of waste stream
Performance Goals and Targets		
Metrics	• Low energy input processes • Separation technologies • Elimination of gas flaring—50% reduction of process waste	• Spin-off companies—increase jobs • Reduction of waste to landfill or land dispersion of waste
Potential Participants and Roles		
Stakeholders	Industry/Users: supply waste stream, economies, consulting Industry/Material: supply waste stream, economics, consulting National Labs: validation/economic validation—pilot demo Academia: process develop/basic R&D, pilot/demo process Associations: knowledge base-outreach	

Impacts

Saves energy: low - Not an energy reduction (low cost feedstock)
Reduces carbon, wastes, emissions, water: high - Using waste productively
Accelerates innovation: high - New process development
Reduces costs: high - Uses low cost feedstock for new material
Improves product quality: low
Improves competitiveness: high - Low cost feedstock
Increases raw material efficiency / yields: high - Low cost feedstock, reduces waste

Figure A-4. Novel Separations

KEY CHALLENGES:	DESIRED OUTCOMES:
• High cost: large fraction of total processing cost is in separations (CAPEX and OPEX) • Low efficiency (loss of product) • Reliability (e.g., membrane fouling)	• Cost effective and highly efficient separations technologies

	Robust and Selective Membranes	Process Intensification to Reduce and/or Eliminate Separations
R&D Approach		
<3 years	• Apply targeted R&D in polymeric materials for membrane application • Basic research on ceramic inorganic/zeolite membranes • Computational materials science applied to membrane materials (organic and inorganic) • R&D to understand basics of membrane fouling	• R&D on process chemistry and reaction conditions including catalysis (biological and thermochemical) • Engineering development for process equipment and systems • Process simulator and modeling
>3-5 years	• Apply new polymeric materials to targeted separations • Scale up of zeolite membranes • Validate lab-scale results in industrial setting • Apply results of focused studies at pilot and demonstration scale	• Development of new novel unit specifications that combine reaction and separation • Pilot and demonstration of novel technologies
Performance Goals and Targets		
Metrics	• Reduce energy consumption by x% • Lower GHG footprint % • Increase product recovery efficiency by x% • Reduce water utilization and consumption by x%	• Reduce energy consumption by x% • Lower GHG footprint % • Increase product recovery efficiency by x% • Reduce water utilization and consumption by x%
Potential Participants and Roles		
Stakeholders	Industry/Users: Bio-manufacturers (e.g., ADM, DuPont, Koch, Tate and Lyle) Industry/Material. Same as above National Labs: NREL, PNNL, ORNL, ANL, LANL Academia: Too many to name Associations: –	

Impacts

Saves energy: high
Reduces carbon, wastes, emissions, water: high
Accelerates innovation: high
Reduces costs: high
Improves product quality: high
Improves competitiveness: high
Increases raw material efficiency / yields: high

B. Reduction of Waste in Manufacturing Processes

Vision and Goals

FOCUS QUESTION 1: *In the next five years, what goals would we like to achieve to reduce waste and enable reuse of waste material in manufacturing processes? What are some of the specific targets we would like to reach?*

Table B-1 summarizes participant comments on the vision and goals they would like to strive toward to reduce waste in manufacturing processes.

Table B-1. Vision and Goals
Water Resource
• Reduce the cost of industrial water treatment by 50% • Reduce water usage in manufacturing processes by 20% • Reduce industrial water usage by 20% by 2020 • Achieve zero water discharge from industrial operations by 2035
Reduce Scrap/ Sub-par Parts
• Reduce off-spec product manufacturing by 10% • Reduce new material waste by 10% • Increase production of in-spec goods by 20% via solving issues of crack formation in solid-liquid transition (this may occur during welding and additive manufacturing) • Reduce metals going to landfills by 40% by 2030. This goal includes all metal elements from all possible sources • Increase in-plant scrap reduction and recyclability • Achieve net-zero waste to landfill • Increase the value of scrap/waste metal, so that the net cost of reducing scrap/waste metal is 0 and/or the value of scrap/waste metal reuse is doubled
Design & Manufacturing Process
• Achieve 25% energy intensity reduction in 10 years • Reduce energy use for separation from 22% to 17% in 5 years • Reduce coolant fluids for metal work by 50% • Design products that can be 50% reused and/or 50% recycled • Eliminate post-mechanical processing of (near) net-shaped formed products • Increase waste heat recovery by 20%
Reuse
• Increase scrap reuse two-fold by 2020 • Reclaim 100% of all web materials in 2D manufacturing • Turn carbon fiber pre-press scrap into a semi-structural part for aerospace or automotive. Currently, 30% of the carbon fiber is wasted as pre-press scrap • Smart recycling of spent aerospace grade alloy
Enterprise View
• Achieve enterprise-wide strategy to implement sustainable technology so all tiers can react to it

Challenges & Barriers

FOCUS QUESTION 2: *What are the key challenges/barriers to develop technologies that either reduce waste or increase the reuse of waste in manufacturing processes? What are the problems we are trying to solve?*

Table B-2 summarizes comments on the key challenges and barriers to reduce waste or increase the reuse of waste in manufacturing processes. Workshop participants were asked to vote on the challenges and barriers they perceived as most important. The number of votes received (indicating participants' highest priorities) is shown by asterisks and the vote count is in parentheses.

Table B-2. Challenges and Barriers
Process Understanding
• Lack of complete understanding / characterization of process **(2)
Technology
• Lack of availability of select sensors/ smart process equipment which enables process control*****(5) • There is a gap in NDE to access material properties for reuse • Cost of water is too low • Cost is prohibitive for full development and deployment of technologies for reduced material use, such as technologies on for scrap separation • Lack of cost efficient and mature smart data acquisition for developing feedback control loops and health • Limited monitoring of process inputs • Process/tech gaps and challenges to re-engineers and cost efficient recycling of spent finished products******(6) • Lack of scrap separation technology to accommodate complex and varied alloys/materials. These complex materials must be separated during recycling before they can be reused**(2) • Lack of understanding in the fundamental material processes in specific manufacturing environments*(1)
Knowledge Gap
• Lack of open knowledge of industry specific "waste" footprints to facilitate innovation and entrepreneurship ********(8) • Lack of reliable data on material flow • For reduction, recycling, or reuse of water, innovation and fundamentals pipeline is not well supported**(2) • Lack of publically available benchmarking data*******(7) • Intellectual property is preventing data sharing and cooperation between companies*(1)
Test-Bed/ Demo Facility
• Lack of test-beds and/or modular systems that enable integration of emerging technologies at intermediate scale to demonstrate performance, cost, & lower risks******(6) • For water related application, pilot demonstration results are poorly reported
Stakeholder Buy-in
• Insufficient corporate buy-in for developing and adopting technologies in current environment**(2) • Inability to quantify benefits and ROI • Poor understanding in the economics of sustainable manufacturing. Specifically, stakeholders are unable to identify or discern processes that are profitable for industry, includes collection processing and sale of products**(2) • Stakeholders are not incentivized to design products for sustainable manufacturing; they are only motivated to design products to promote product sales • Insufficient knowledge in manufacturers and consumers to understand difference between up-front cost (profit) and life cycle cost***(3)

Table B-2. Challenges and Barriers
Certification and Qualification
• The timeline to certify and quality a new technology is too long. Even for an existing product; if this product was to be modified, if only slightly, it will need to be recertified and reapproved. Included are ISO and PPAP certifications*(1)
Cost
• Insufficient funding to research, develop, and deploy new sustainable manufacturing technologies ***(3) • Lack of commitment (due to lack of understanding or poor management), resource limitation, lack of education & training****(4)

Research & Development Needs

FOCUS QUESTION 3: *Drawing on the technical challenges identified, what critical R&D is needed to overcome the major challenges, address scalability, and advance new technologies to reduce waste in manufacturing processes?*

The highest priority R&D needs were derived from the most significant barriers and challenges identified in Table B-2. In the following pages, Figures B-1 through B-4 present an analysis of the highest priority R&D topics for *Reduction of Waste in Manufacturing Processes*.

Figure B-1. Smart Process Control

KEY CHALLENGES:	DESIRED OUTCOMES:
• Minimum or no direct measurements of key manufacturing parameters • Process too complex to adjust and modify in real time • Too many variables to monitor and assess • Process not well understood • Sensor response time is too slow	• Real-time measurement of complex processes • Ability to characterize complex, multi-variable process • High-speed sensors with large data protocol capability • Cost-effective approaches • Developed training curriculum • Proven high performance NDT sensors

	Sensors	Control Loop
R&D Approach		
<3 years	• Identify sensor performance requirements • Develop prototype sensors	• For a given process, fully characterize and model for predictive behavior • Understand inputs and effects on outputs
>3-5 years	• Validate and verify sensor performance under appropriate conditions • Low-rate production and deployment of sensors	• Finger prints for complex processes • Reduce sensor set for real-time process control
Performance Goals and Targets		
Metrics	• Low cost • Real time data collection capability, with consistent and reliable measurement • Fast-large data reduction or simple, quick surrogate measurements	• Complete understanding of process physics, inputs and outputs • Reduced sensor set

Potential Participants and Roles

Stakeholders

Industry/Users: Help define process commitments
Industry/Material: Integration, material knowledge
National Labs: Computational expertise, method development, sensor
Academia: R&D, process-physics understanding
Associations: Standards development, user groups
Other: N/A

Impacts

Saves energy: Medium – Effective system, reducing waste
Reduces carbon, wastes, emissions, water: Medium –
Accelerates innovation: High – Transforming with better understanding for innovation
Reduces costs: Medium –

Improves product quality: High – significant
Improves competitiveness: High
Increases raw material efficiency yields: High –

Figure B-2. Metrics for Open Waste Inventory

KEY CHALLENGES:	DESIRED OUTCOMES:
• Lack of open knowledge of industry specific waste footprint and energy • Lack of ability to measure • Lack of motivation of company to measure • Can this be done at unit level vs plant level • Concern over dissemination of proprietary knowledge	• Open database of information that is industry aggregated • Accepted format for reporting • Case studies of industry footprint (to be taught in business school and on the job training) • Tie waste inventory to lean activities • Disseminate best practices and improvement opportunities

R&D Approach

<3 years

- Develop framework for reporting, dissemination access, and get industry buy-in on how to anonymize and secure
- Identify, develop, adapt reporting metrics and prototype with companies
- Engage associations
- Limited non-disclosure agreement access

>3-5 years

- Open access to data
- Expand each to more companies
- Research conversion symbiosis opportunities to increase value of waste
- Document best practices

Performance Goals and Targets

Metrics

- Data from 1000's of companies across broad a section of NAICS codes
- Waste reduction targets cited in corporate reports
- Development of course offerings at universities associated with how to use data to reduce waste generation
- SBIR/STTR offerings to address specific opportunities to reduce waste emissions and potentially monetize
- Development of workforce level training modules/workforce certification

Potential Participants and Roles

Stakeholders

Industry/Users: Provide data/identify opportunities, consumer training, new business technology suppliers
Industry/Material:
National Labs: Promote/support metrics and standards research; promote company participation
Academia: Develop metrics/research, case studies
Associations: Support standard and promote in their segments
Other: N/A

Impacts

Saves energy: Low to Medium – Energy savings are indirect though waste reuse
Reduces carbon, wastes, emissions, water: Medium
Accelerates innovation: Medium to High – Promote small companies to develop technology or waste trading opportunities
Reduces costs: Medium to High – Reduce waste handling costs
Improves product quality: Low
Improves competitiveness: Medium – More cost effective, identifies opportunities for material substitution
Increases raw material efficiency yields: Medium – Identifies opportunities for more reuse at higher value levels

Figure B-3. Testbed Modular Systems that Enable Integration of Energized Technologies to Demonstrate Performance, Cost, and Lower Risk

KEY CHALLENGES:	DESIRED OUTCOMES:
• Lack of intermediate performance data for promising low-mid TRL technologies • Limited industry funds for in-house pilot testing • Industry concern about risk and cost of new technology	• Industrial adoption of the technology • De-risked innovative technology • Better understanding of technology advantages and performance data shared among industries • Trained workers and students • Industry leverages outside resources to advance technology

Test Bed Modular Systems

	R&D Approach
<3 years	• Evaluate and prioritize the promising technologies to advance • Develop metrics • Design, construct and acquire facilities • Compare vastly different technology spaces to pilot and look for broad impact
>3-5 years	• Fund pilot demonstrations • Report results • Transfers technology to industry
	Performance Goals and Targets
Metrics	• Three pilots greater or equal to one tenth scale • Achieve 50% reduction in cost of established process
	Potential Participants and Roles
Stakeholders	Industry/Users: Provide challenge to invest Industry/Material: Provide technology National Labs: House and test processes; technical expertise Academia: Students, innovation Associations: Oversight, dissemination of results Other: N/A

Impacts

Saves energy: Medium – Enables adoption of energy saving technology
Reduces carbon, wastes, emissions, water: High – Directed at waste/recycling technology
Accelerates innovation: High – Adoption of new technology
Reduces costs: High – Adoption of new technology
Improves product quality: Low
Improves competitiveness: Medium – Gets new technology into the market, launches new companies
Increases raw material efficiency yields: Low

Figure B-4. Stakeholder Engagement

KEY CHALLENGES:	DESIRED OUTCOMES:
• Lack of incentives for developing/studying sustainable manufacturing • Lack of industrial commitment/openness • Poor understanding of the economics of processes, collection, products • Lack of good business models	• Develop an institute for sustainable manufacturing • Encourage industry to invest • Clear understanding of sustainable manufacturing processes, collection, products • Define industrial focused business model • Identify incentives for industry to pay for efforts

Test Bed Modular Systems

R&D Approach	
<3 years	• Identify resource needs • Establish stakeholder involvement • Develop business model
>3-5 years	• Share resources among industry • Stakeholder involvement that is stronger than government and academic groups • Execute the business model
Performance Goals and Targets	
Metrics	• Build a resource team • Ability to leverage industry knowledge base
Potential Participants and Roles	
Stakeholders	Industry/Users: Provide knowledge, provide test areas Industry/Material: Provide design bases for systems National Labs: Contribute to design of systems Academia: Provide basic support for processes Associations: None Other: Emulate energy efficiency programs in a low transaction process (Energy Trust of Oregon is an example)

Impacts

Saves energy: High
Reduces carbon, wastes, emissions, water: High
Accelerates innovation: Medium
Reduces costs: High

Improves product quality: Medium
Improves competitiveness: Medium to high
Increases raw material efficiency yields: Medium

C. Sustainable Design and Decision-Making

Vision and Goals

FOCUS QUESTION 1: *In the next five years, what design tools, guidelines, and other resources would we like to have for sustainable design and decision-making?*

Table C-1 summarizes participant comments on the vision and goals that they would like to strive toward in sustainable design and decision-making.

Table C-1. Vision and Goals
Tools

• Life cycle planning tool
• Advanced simulation tool for developing sustainable design
• Tool to convert data into information that is understandable to public
    • Actionable intelligence available to policy makers at different levels; what is value proposition. e.g., machine learning tool
• Flexibility (tools)
    • Variation in metrics/weightings
    • Variation in industries, sectors, products, etc.
• Develop multiscale integrated design tools that can integrate sustainability assessment function into it
• Unified techno-economic financial tool (e.g., H2A for H2), including recycling and environmental impact and sustainability in general
• Ease of use of tools/software across the organization
    • Various inputs to decisions at all levels
• Tool for externalities

Social/Culture
• Need for integrated approach   • How to prioritize goals • Goal: Help individual industry elements understand the ‘benefits’ of sustainability • Remove economic threat risk: mitigate risk • Training for all level of employees in a manufacturing firm
Design

• Design for EOL first
    • Product EOL strategy
    • Information to EOL industry strategy
• Design for remanufacturing and end-of-use management
• Develop new paradigms for:
    • Ease of reuse
    • De-manufacturing
    • e.g., (wiki) database of (recycle friendly alloys) materials properties/specifications so industry can be informed about these as an option

Program/Guideline
• DOE should expand the Better Plants program to set goals and commitments related to sustainability • DOE and DOC should develop “incentives” or “credit” schemes to drive new investments • Guidelines for estimating (valuing) market externalities, e.g. health care costs

Table C-1. Vision and Goals
Data
• Vision: Have accessible data, information, tools that enable manufacturers to value sustainable materials/products/processes • Develop performance metrics to value sustainability beyond economics • Database of materials/specifications and guidelines for sustainable design selection • "Free", easy to use database to support environmental accounting/LCA. e.g., electronics printer manufacturing, "MITPAIA". • Federal agency reports on energy require background information to be public • Information platform to allow stakeholders (e.g., recyclers, manufacturers) to exchange information on product design and recycling technologies, etc. The problem is the lack of information sharing/communication
Other Overarching
• Companies will make decisions that reduce use (including externalities)   • Systems tools feedback to design

Challenges and Barriers

FOCUS QUESTION 2: *What are the key challenges/barriers to developing tools, design guidelines, and other resources for sustainable design and decision-making?*

Table C-2 summarizes participant comments on the challenges and barriers that need to be addressed as we strive toward sustainable design and decision-making. Workshop participants were asked to vote on the barriers and challenges they perceived as most important. The number of votes received (indicating participants' highest priorities) is shown by asterisks and the vote count is in parentheses.

Table C-2. Challenges and Barriers

Communication

- Disconnect between design and EOL ***(3)
- Lack of information sharing among stakeholders (e.g., recyclers, manufacturers) impedes achieving sustainable manufacturing *(1)
- Communication across supply chains
    - Confidentiality/IP

Data

- Open access/wiki data and tools may not be a viable business model (collaboration missing). Manufacturing data is competitive intelligence/advantage. Companies will not easily release this data to support "free" tools. Neutral space needed. ********(8)
- Lack of data *****(5)
    - Confidentiality/IP
    - Development of new/novel processes
- How to quantify externalities, e.g. CO2 emissions ***(3)
- Lack of data that is at multiscale and multi-dimension through the life cycle **(2)

Tools

- Integration of design tools (at the material, product, process and ecosystem level) **********(10)
- Lack of integrated Design for X (DfX) tools ****(4)
    - Design for manufacturing, remanufacturing, recycling, etc.
- Decisions made by companies are unique—hard to develop tools that are broadly applicable ***(3)
- Need a goal setting tool
- How do we use machine learning as a tool? Use available data. Make accessible to public.

Analysis/Scale

- Lack of knowledge of sustainability at microscale (molecules) **(2)

Incentives/Awareness

- Philosophy of current design and industrial production community that sustainable design will increase unit production cost (not thinking life cycle) ****(4)
- Technology to empower workers to engage the sustainable manufacturing worker as a decision maker **(2)
- Lack of industry and public understanding of the balance of triple bottom lines in sustainable design and manufacturing *(1)

Design

- Design decisions are made within stovepipes **(2)
- Certification of changes to existing product (takes years) *(1)
- Designers do not make final decisions - they have boundaries
- Alternatives for design are not available with safer materials

Table C-2. Challenges and Barriers
Processing
• Need to rethink: material ease of reuse, re-manufacturing **(2) • Lack of knowhow and enabling technology (industry to develop knowhow) **(2)
Workforce/Culture/Social

• Externalities (and pesky problems like rebound) are at odds with company's interest **(2)
    • Incentives-related
    • Information for policy-makers
    • Worker and other social issues
• How to sustain workers to continue their jobs—job skill relevance, e.g. robotic manufacturing
• Need for work force with systems thinking perspective: How does what I do have broader impact?

Supply Chain
• Transparency of supply chain data (near-real time data) *******(7) • Increased risk and uncertainty inherent in developing sustainable supply chain (life cycle security) ****(4) • Significant variability across the supply chains *(1) • No U.S. supply chain option • Lack of continuous feedback information loop, EOL feedback
Guidelines

• Need new replicable model for eco-system model; reproducing capability for each industry **(2)
    • e.g., environmental cycle, automotive cycle; they work, we need a new model
• Volume and variability of material. Need someone to validate performance of material * (1)
• ISO Standards for life cycle analysis/environmental product declarations (EPD) are insufficient to capture externalities (for validation, verification)
    • All drivers are not captured
• Need for policy makers to understand (or have the tools to assess) the complex industry landscape (web of industry)

R&D Needs

FOCUS QUESTION 3: *Drawing on the technical challenges identified, what critical R&D is needed to overcome the major challenges, address scalability, and advance new technologies in sustainable manufacturing?*

Table C-3 summarizes discussions on the critical technology R&D that will be required for sustainable design and decision-making. The highest priority R&D needs were derived from the most significant barriers and challenges identified. The number of votes received (indicating participants' highest priorities) is shown by asterisks and the vote count is in parentheses. In the following pages, Figures C-1 through C-5 present an analysis of the highest priority R&D topics for *Sustainable Design and Decision-Making*.

Table C-3. R&D Needs
Highest Priority R&D Needs

• Integrated decision-making design tools **************(14)
  ◦ Across lifecycle of product
  ◦ Safer materials/alternatives
• Open access data *************(13)
  ◦ Wiki
  ◦ IP
• Transparent, up-to-date supply chain data *******(7)
  ◦ Verified data
  ◦ Validated data
• Reduction of supply chain risk ****(4)
• Look at life cycle cost ****(4)
  ◦ Workforce
  ◦ Incentives
  ◦ Other

Other R&D Needs

• Replicable tool development process
  ◦ Integrated tool for end of use
• Integrated with manufacturing process
• Develop validation technologies
• Need policy tools that transfer responsibilities between stovepipes
• Safer materials
  ◦ Alternatives for designers
  ◦ Lack of chemical ingredient information
• Information feedback loop continuous
• Policy and regulation insufficient, need "producer responsibility"
• Arm original designers with material life-cycle cost, manufacturing geography and recyclability options to enable full life plans upfront/in design process
• Development of generic, intelligent decision making tools for sustainable manufacturing

Figure C-1. Data and Expert System for Transparent Supply Chain Analysis

KEY CHALLENGES:	DESIRED OUTCOMES:
• Data collection and availability for quantifying sustainability is lacking • Aggregation of data throughout the supply chain is a challenge • Up to date data is key, but missing • Data security and IP can discourage cooperation	• Designer awareness of trade-offs of design alternatives • New companies/economic development with new activities • Innovations in supply chain management approaches • Ability (and accountability) to incorporate sustainability into manufacturing

Data Management Systems

R&D Approach	
<3 years	Data management systems: • Computational and software framework for data aggregation, respecting privacy/IP • Increase use of sensors in manufacturing to gather granular data on processes • Expert systems to support decisions for sustainable manufacturing processes
>3-5 years	• Pilot programs for increasingly complex supply chains • Development of a certification program to verify/validate data • Enhance expert system with policy/regulation/markets/social aspects and domains
Performance Goals and Targets	
Metrics	• Better capability to define and measure sustainable manufacturing across supply chain and entire life cycle • Expand accessibility of system to policy makers
Potential Participants and Roles	
Stakeholders	Industry/Users: Collect data, verify; end users-design, certify products; case studies Industry/Material: Identify data gaps and needs National Labs: Develop framework, validate collection efforts Academia: Provide best practices for developing framework; workforce training; case study development with industry Associations: Garnering support for industry; organize data collection efforts Collaboration: Need a multi-partner initiative to develop framework, gets buy-in, develop roadmap for demonstration and deployment; researches and communicates value to industry and energy bottom line

Impacts

Saves energy: high, Identifies losses/hotspots and embodied energy in products
Reduces carbon, wastes, emissions, water: high, Identifies losses/hotspots and embodied energy in products
Accelerates innovation: high, Increases awareness of sustainability and business opportunities
Reduces costs: low, Could increase costs due to data requirements

Improves product quality: low, N/A
Improves competitiveness: medium, Creates market advantage potential for new companies
Increases raw material efficiency/yields: high, Identifies hotspots and alternatives
Other: high, Validates energy, materials savings

Figure C-2. Open Access Data

KEY CHALLENGES:
- Lack of a database
- Lack of culture/system of sharing data

DESIRED OUTCOMES:
- Proper model for sharing data
- Availability of database
- Easy updating system

R&D Approach

<3 years
- Proper system for circulation of data
- IP agreements to address the confidentiality of data
- Manufacturing database
- Material database (including cost)
- Viability of data
- Data management

>3-5 years
- Database for each industry
- Proper regulation for publishing old data (the same as patent law)
- Policy for updating data

Performance Goals and Targets

Metrics
- To develop a model for sharing and using updated data by considering rights of data owners (similar to patent procedure and regulation)

Potential Participants and Roles

Stakeholders

Industry/Users: Responsible use of data available in the open system; provide feedback
Industry/Material: Sharing available data on the open system
National Labs: Contribute to update data; contribute to validate data
Academia: Responsible use of data; provide feedback; sharing available data
Associations: -

Impacts

Saves energy: *None stated*
Reduces carbon, wastes, emissions, water: *None stated*
Accelerates innovation: *None stated*
Reduces costs: *None stated*
Improves product quality: *None stated*
Improves competitiveness: *None stated*
Increases raw material efficiency / yields: *None stated*

Figure C-3 Integration of Sustainable Design and Decision-Making Tools

KEY CHALLENGES:	**DESIRED OUTCOMES**:
• Many individual tools exist, but do not integrate well • Individual tools often require specific expertise • What kind of metrics (indicators) need to be considered? • How to present information in a way the designer can handle? • How can triple bottom line objectives be optimized/balanced?	• Tools should allow the decision maker to input sustainable manufacturing objectives/constraints • Tool needs to incorporate transparent, validated data from across the supply chain (materials, energy, etc.) • Tool can provide design alternatives with associated sustainable manufacturing information to support decision making

Integration of Disparate Tools

	R&D Approach
<3 years	Integration of disparate tools: • Define existing tools and gaps • Define overlapping capabilities and/or opportunities for linking tools • Define metrics/indicators that must be integrated into models/tools Sustainability assessment models
>3-5 years	• Integrate sustainability assessment models into new/existing tools • Develop models to quantify metrics/indicators • Develop mechanism for data entry/update
	Performance Goals and Targets
Metrics	• Repository of methods/tools • Data warehouse accessible to industry/academic decision makers
	Potential Participants and Roles
Stakeholders	Industry/Users. *None stated* Industry/Material. *None stated* National Labs. *None stated* Academia. *None stated* Associations. *None stated*

Impacts

Saves energy: *None stated*
Reduces carbon, wastes, emissions, water: *None stated*
Accelerates innovation: *None stated*
Reduces costs: *None stated*
Improves product quality: *None stated*
Improves competitiveness: *None stated*
Increases raw material efficiency / yields: *None stated*

Figure C-4. Life Cycle Cost: Incentives, Regulation, and Work Force Development

KEY CHALLENGES:	DESIRED OUTCOMES:
• Work forces are not engaged in decision making • Current philosophy is to focus on unit cost vs. life cycle cost • Lack of policy, regulations, incentives to properly value sustainability	• Enabling technologies/tools allow engagement at all levels of work force • Manufacturers use life cycle cost analysis to evaluate product cost and decision making • Workforce training and development occurs at designer/engineering level • Workforce training and development occurs at shop floor level • Government properly incentivizes manufacturers to incorporate sustainable design • Government creates policies and regulations to set goals for sustainability – "by X%"

	Life Cycle Costs/Work Force Development	Incentives Regulation
R&D Approach		
<3 years	Life cycle cost tool development: • Develop tool to translate operating parameters into life cycle value • Develop tool to create product based on life cycle analysis • Create needed training to allow engineers/technicians to see impact of decisions	Incentives, regulation: • Create a platform for incentivized sustainability for manufacturing • Create a platform for policy and regulations (including goals) to promote sustainable manufacturing
>3-5 years	• Integrate tool into process operation • Integrate tool into product decisions • Ensure entire work force is trained on the impact of decisions on sustainability	• Insert incentivized language in Congressional bills • Insert policy and regulation language (including goals) into appropriate orders
Performance Goals and Targets		
Metrics	• *None stated*	
Potential Participants and Roles		
Stakeholders	Industry/Users. *None stated* Industry/Material. *None stated* National Labs. *None stated* Academia. *None stated* Associations. *None stated*	

Impacts

Improves product quality: high
Improves competitiveness: high
Increases raw material efficiency / yields: high
Other: – high, Worker satisfaction

Figure C-5. Reduction of Supply Chain Risks

KEY CHALLENGES:	DESIRED OUTCOMES:
• Resilience • Consistently meeting performance targets • Ability to adapt to production volume (scale) • Technology readiness	• Ability to meet production target under different conditions • Ability to handle market fluctuations without cost penalty • Meeting acceptability levels • No PR disasters

Topic

R&D Approach	
<3 years	• Metrics for decision making • Assessment tools for technology readiness and criticality • Multiple suppliers development
>3-5 years	• Supplier integration • Strong metrics for assessment • Ability to model supply chain performance and risks
Performance Goals and Targets	
Metrics	• Effective certifications • Comprehensive modeling tools for supply chains • Having assessment tools of risk and resiliency
Potential Participants and Roles	
Stakeholders	Industry/Users. *None stated* Industry/Material. *None stated* National Labs. *None stated* Academia. *None stated* Associations. *None stated*

Impacts

Saves energy: *None stated*
Reduces carbon, wastes, emissions, water. *None stated*
Accelerates innovation: *None stated*
Reduces costs: *None stated*

Improves product quality: *None stated*
Improves competitiveness: *None stated*
Increases raw material efficiency / yields: *None stated*

D. End-of-Life Product Management

Vision and Goals

FOCUS QUESTION 1: *In the next five years, what goals would we like to achieve to improve reuse, recycling and remanufacturing or make product disassembly more efficient? What are some of the specific targets we would like to reach?*

Table D-1 summarizes participant comments on the vision and goals for EOL product management.

Table D-1. Vision and Goals
Upcycling
• Develop efficient and effective systems to upcycle 20% more waste • Matured infrastructure and technology enablers for remanufacturing to increase recovery intensity • 100% recovery of designated critical materials by 2025
Waste Reduction
• Reduce manufacturing waste entering landfills by 50% or greater by 2020
Strategic Guidance
• Clear federal government leadership in procurement of sustainable chemical goods and 100% collection; clearly communicated to public by 2020 • Improved communication and information sharing between/among manufacturers and the various stakeholders in product end-of-use (e.g., recyclers, refurbishers, remanufacturers) • Federal guidance on including EOL cost in product pricing
Design for EOL
• Every product has an EOL plan produced by the designer • Eliminate solid waste disposal as an EOL option for management • In 5 years, extend functional life of industrial coolants/lubricants by 10x; in 15 years, achieve 100% reuse via a closed system • Design product to achieve 100% disassembly • Developed metrics and indicators that account for marketplace value and application
Collection
• Collect 100% of EOL products in a cost effective way • Mature framework for EOL collection (support party with primary source) • Mature reverse-logistics path optimizes value and policy for 100% of EOL products • Fully developed efficient EOL collection system for North America
Separation/Recovery Technology
• Composite matrix that allows 100% fiber recovery in a cost and environmentally effective manner • Technology that melts down additive manufacturing parts and separates component metals materials to 98% purity

Challenges and Barriers

FOCUS QUESTION 2: *What are the key challenges/barriers to develop technologies that either improve reuse, recycling and remanufacturing or make product disassembly more efficient? What are the problems we are trying to solve?*

Table D-2 summarizes participant comments on the challenges and barriers to EOL product management. Workshop participants were asked to vote on the challenges and barriers they perceived as most important. The number of votes received (indicating participants' highest priorities) is shown by asterisks and the vote count is in parentheses.

Table D-2. Challenges and Barriers

Business Model

- Uncertainty in how to incorporate recyclability into process development, especially for additive manufacturing
- Cost of material does not represent the "total" cost of material*******(7)
- Recycling costs not included in initial product price to consumers
- Low cost of many raw materials prevents a paradigm shift from "how we have always done it" to an EOL paradigm
- Uncertainty on availability and cost in the future of resources, and the potential international competition for resources*(1)

Workforce

- Lack of training and educated workforce to execute the work at all levels********(8)

Policy

- Highly fragmented program and policy frameworks for consumers, EOL manager, and industry owners to navigate, supply and adding cost to recyclers

Incentive

- Lack of EOL acceptance by builders and contractors
- Lack of incentives and drivers for design for EOL *****(5)
- Lack of investment to improve current methods for product collection **(2)
- Irrational conception of residual value in EOL products by consumers
- Lack of education for consumers on the value of sustainability *(1)

Product Design

- Lack of EOL standards and design values
- Lack of
    - Design rules for design for EOL
    - Integrated design tools that facilitate EOL design
- Devices are becoming less modular and cannot be efficiently disassembled and separated
- Design conflicts between what the consumer wants versus what facilitates EOL management. For example, consumer electronics are designed for smaller size formats, but not environmentally survivable ********(8)

Metrics

- Lack of methodology to quantify environment or social costs and benefits**(2)
- Improved metrics needed to measure recycling efficiency (beyond mass based metrics)***(3)

Technology

- Separation processes need to be developed for emerging materials, such as those used in additive manufacturing materials or composites**(2)
- Lack of fastening systems allowing disassembly of buildings
- Lack of effective technology to separate hybrid composites and mixed material *****(5)
- Immature technology development for composites recycling. Additional work needed to understand the

Table D-2. Challenges and Barriers
chemistry needed to break down the thermoset matrix to enable composite recycling • Insufficient capabilities for rapid separation and identification of materials******(6) • Lack of infrastructure for collection and separation technology**(2) • Lack of efficient technology to separate and recover mixed metals**(2)
Knowledge
• Lack of awareness and information about product attributes, such as composition, re-manufacturability, recyclability, and markets for materials isolated from products********(8) • Lack of knowledge of opportunities in other fields. “Industry is too specialized” • NAICS codes too narrow for better product definition
Funding
• Lack of funding to develop recycling processes; pushing technology development to other countries*******(7)
Ecosystem
• Immature ecosystem that facilitates engagement between EOL products and remanufacturers/recyclers*(1) • Information sharing mechanism between manufacturers and EOL management companies****(4)

Research & Development Needs

FOCUS QUESTION 3: *Drawing on the technical challenges identified, what critical R&D is needed to overcome the major challenges, address scalability, and advance new technologies to enhance end-of-life product management?*

The highest priority R&D needs were derived from the most significant barriers and challenges identified in Table D-2. In the following pages, Figures D-1 through D-5 present an analysis of the highest priority R&D topics for *EOL Product Management*.

Figure D-1. Identification and Separation of EOL Products for Recycling

KEY CHALLENGES:	DESIRED OUTCOMES:
• Lack of capability to separate heterogeneous/ multicomponent materials with high purity • Need to meet final material specification • Stringent cost/energy/hazardous waste requirements	• New rapid and robust screening technologies • Automated and highly accurate sorting systems • Separation technologies that have low environmental impacts, energy use, and cost intensity • Impact product design for efficient recovery

	Identification Technology	Separation Technology
R&D Approach		
<3 years	• Product design for EOL material identification • Standards and surrogate development • Evaluate existing identification technologies	• Develop closed loop chemical separation process
>3-5 years	• Develop unique material targets • Develop new identification technologies	• Develop closed loop separation technologies with zero undesired by-products • Develop low temperature metal separation
>5 years	• *None stated*	• *None stated*
Performance Goals and Targets		
Metrics	• Identify 90% of all EOL product materials	• 99% recovery and reuse of chemicals used in recycling process • 99% separation of metals
Potential Participants and Roles		
Stakeholders	**Industry/Users:** Scale-up expertise, cost analysis, technology and material acceptance **Industry/Material:** IT companies to mark and identify materials **National Labs:** Demonstration facilities develop and test sensors and tagging technologies **Academia:** Basic research and student/workforce training **Associations:** Standards, communications, changing culture **Other:** Consumer groups, government regulation	

Impacts

Saves energy: Medium – Less virgin material processing
Reduces carbon, wastes, emissions, water: Medium – Less processing
Accelerates innovation: High – New technologies developed
Reduces costs: Medium – Reduced cost of virgin material
Improves product quality: Low
Improves competitiveness: Medium
Increases raw material efficiency yields: High – Reusing material many times
Other: High – Resources available for future generations

Figure D-2. Incorporating the Recycling Cost in the Product Cost

KEY CHALLENGES:	DESIRED OUTCOMES:
• Not all products have a net positive EOL value • Lack of economies-of-scale that drives a net positive EOL value • Virgin materials are often artificially lower/similar in cost to recycled materials • No clear path to promote recycling via incentives, taxes, or penalties • Lack of local infrastructure for recycling/reuse	• Capture toxic waste • National uniform system • Real cost of materials includes EOL and environmental costs • Consumer education for a culture shift • Market driven by fully burdened costs • Market driven from both ends: consumer and industry

	Methodology for Fully Burdened Cost	Standardized Collection System & Education
R&D Approach		
<3 years	• Survey industry and create clear accounting of all compounds and fully burdened cost • Evaluate cost-benefit of current recovery program • Identify current recycling methods and systems • Identify gaps in product category recycling	• Survey and evaluate consumer behavior • Survey and evaluate current infrastructure • Survey and evaluate current recycling and reuse programs
>3-5 years	• Develop system for including fully burdened cost of product • Identify where in the value chain fully burdened cost is accounted for • Establish pilot programs for specific products • Short and long-term costs established for recycling/recovery accounting for economy of scale	• Establish clear list of high and low externalities cost of products • Establish best practices • Establish pilot programs
Performance Goals and Targets		
Metrics	• Greater transparency of components and their costs • Establish the most efficient accounting of externalities and association in the value chain • OEM's change design culture to include fully burdened costs	• 50% increase in awareness and partner patron of /by consumers in recycling programs • Consumers understand true costs

Potential Participants and Roles

Stakeholders

Industry/Users: Provide data and current methods
Industry/Material: Evaluate recycling cost at scale
National Labs: In-kind cost share by hosting center
Academia: Data collection, value mapping
Associations: CES, ISRE and other trade organizations of industrial and consumer products
Other: Regulatory agency

Impacts

Saves energy: High – Externalities are priced in
Reduces carbon, wastes, emissions, water: High – Externalities are priced in
Accelerates innovation: Medium – Could change from incremental innovation to paradigm shifts
Reduces costs: Increase short-term cost but decrease long-term cost, overall decrease in fully burdened cost

Improves product quality: High – Sustainable products with longer life
Improves competitiveness: High – Sustainable products
Increases raw material efficiency yields: High – Products last longer and materials reused
Other: Cleaner environment prevents environmental disasters/surprises

Figure D-3. Metrics

KEY CHALLENGES:	DESIRED OUTCOMES:
• Current mass-based recycling metrics do not measure environmental benefits for different materials • Current metrics do not measure material loss in processing • Difficult to measure out of service product in home storage	• A simple and accepted set of metrics for the environmental benefits for specific materials in a program that recycles products • Comprehensive information from all recyclers on a material by material basis • Accounting system for tracking materials down the recycling chain for use on a material and product specific basis

Methodology to Measure Environmental & Social Costs and Benefits

R&D Approach

<3 years

- An eco-footprint like number for measuring the environmental and social impact of the product and recycling outcome. This number would capture all environmental and social costs and benefits into a single number (i.e., energy use, recyclability, toxicity, etc.).

>3-5 years

- A reporting system used by all manufacturers and recyclers of the eco-footprint number for all products
- Presentation of this information to
  1. Consumers at the point of purchase
  2. Designers and manufacturers

>5 years

None Stated

Performance Goals and Targets

Metrics

By 2025:

- 90% of material is recycled at the highest environment and social value
- 50% of consumers are aware of these metrics
- 35% of consumer use these metrics to inform 75% of their purchasing decisions

Potential Participants and Roles

Stakeholders

Industry/Users: Use the metrics for design
National Labs: Develop the metrics
Academia: Develop the metrics
Associations: Develop the metrics
Other: Recyclers use the metrics to report data

Impacts

Saves energy: Medium – Saves embedded energy
Reduces carbon, wastes, emissions, water: High – Big impact from recycling metrics
Accelerates innovation: High – Known system of metrics used by all in place
Reduces costs: Low – May add cost in some cases

Improves product quality: High – Demand by consumers for higher quality and lower environmental impact products
Improves competitiveness: Medium – Informed and caring consumers will make wiser choices
Increases raw material efficiency yields: High – Improved by multiple uses of materials
Other (Societal Actualization): High – Climate change

Figure D-4. Knowledge Enhancement

KEY CHALLENGES:	DESIRED OUTCOMES:
• Lack of awareness of product attributes by recyclers • Lack of informed markets for material from end-of-use products • Lack of a forum for stakeholders to discuss product design	• Forum for stakeholders to discuss design • Improved flow of information between stakeholders • New markets created for material extracted from EOL products • Increased safety in disassembly of end-of-use products

R&D Approach

<3 years	• Convene stakeholders to address information gap • Determine barriers to recyclability and reuse for various products • Assemble teams of stakeholders
>3-5 years	• Designs influenced by end-of-use considerations • Developed framework for sustainable products, assemble companies to close loop
>5 years	• *None Stated*

Performance Goals and Targets

Metrics	• Teams working together to reduce use of virgin material through recycle/reuse of end-of-use products

Potential Participants and Roles

Stakeholders	**Industry/Users:** Share knowledge and perspectives **Industry/Material:** Communicate requirements for product at various stages of life **National Labs:** Broker to facilitate process **Academia:** Share expertise and prior experience **Associations:** Conduit to assemble teams for different stakeholders **Other:** N/A

Impacts

Saves energy: High – Displace virgin materials
Reduces carbon, wastes, emissions, water: Med to High
Accelerates innovation: Low
Reduces costs: Low – Varies by stakeholder and material

Improves product quality: Low – Product should not change quality goal
Improves competitiveness: Medium – High variable
Increases raw material efficiency yields: High – Could drastically reduce raw material
Other: High – Repetition benefit

Figure D-5. Product Design

KEY CHALLENGES:	DESIRED OUTCOMES:
• Lack of design tools integrating EOL considerations • Lack of information related design options • Lack of drivers and incentives • Increasing global markets challenges/drivers • Lack of metrics for evaluation of design options	• Availability of integrated design tools addressing EOL options • Availability of design alternative tradeoffs • Provide users with sustainability evaluation information

R&D Approach

<3 years	• Support R&D for EOL technologies • Develop design tools/methods for remanufacturing/recycling/service. Potential sectors include automobile, aerospace, electronics, and consumer products
>3-5 years	• Develop information hubs for designers on EOL options and tradeoffs • Develop integrated design tool integrating EOL designs
>5 years	• *None Stated*

Performance Goals and Targets

Metrics	• Increase intensity of product recovery • Increase information available on design options and alternatives

Potential Participants and Roles

Stakeholders	**Industry/Users:** Support/implement **Industry/Material:** Support/implement **National Labs:** Support/develop technology **Academia:** Support/develop technology **Associations:** Support **Other:** N/A

Impacts

Saves energy: High
Reduces carbon, wastes, emissions, water: High
Accelerates innovation: High
Reduces costs: high
Improves product quality: Medium
Improves competitiveness: High
Increases raw material efficiency yields: High

E. Materials, Water, and Energy Management

Vision and Goals

FOCUS QUESTION 1: *In the next five years, what sustainability goals would we like to achieve in materials, water, and energy management? What are some of the specific targets we would like to reach?*

Table E-1 summarizes participant comments on the vision and goals to advance sustainability in materials, water, and energy management.

Table E-1. Vision and Goals
Materials

• Materials
    • Renewable feedstock x% (x=25%?)
• Develop markets and supply chains for more sustainable materials
    • e.g., need to drive to economies of scale for alternative materials
• Develop materials and manufacturing methods that do not require oven and furnace heating
    • e.g., out-of-autoclave composites, metal alloy development
• Development of polymeric materials with 3-times use
    • Develop materials that can be used 3 times
    • Ideally processed at low temperature, low water use
• Reduction in amount of landfilled materials by manufacturers by 50% in 5 years
    • e.g., additive manufacturing, or turn into something else

Energy

• Energy management: make efficient use of variable energy sources
    • e.g., from power generation thermal heat storage, or for industrial application
• Peak shifting and grid responsive processes
    • e.g., California steel industry—starts operations after 6 pm
• Energy efficiency—more emphasis on thermal energy, but need to pay attention to mechanical energy

Management/Planning

• Integrated management of water-energy-material where sustainability concerns are properly addressed. Include:
    • Materials target - full development of data/knowledge base about material properties
    • Water-energy source/classification for sustainability assessment

Water
• To find more dynamic and appropriate methods to reduce water usage in electrical generation. Hopefully by half within 5 years. • Reduce industrial water usage 20% in 10 years, 10% in 5 years • ZLD (water efficiency) demonstrated in 5 years • Significant demonstration of a transition from a once through water use to 75% internal recycling • Water/Energy   • Reduce usage/intensity 50% • Water: Reduce industrial consumption by 80% in 10 years (not possible in 5 years) in one industry (including water used in producing imported materials/parts), e.g., chemical separation of metal ores
Process Design

• Integration of low temperature heat reuse in the technical/economic analysis of process
• Reduction of energy consumption by 75%:
    • Using more renewable energy
    • Use more efficient equipment; e.g., SPD glass for buildings

Table E-1. Vision and Goals

- Changing designs (smart design)
- Interdisciplinary integration of different processes

Tools

- Increase industry use of tools that allow for systemic/life cycle analysis of decisions across material/energy/water
    - Integration of economic/environmental criteria

Example Metrics

- Reduce water use intensity over the life cycle, for example:
    - Reduce water use intensity by 20% by 2020
    - Reduce water use intensity by X gallons/unit manufacturing output
    - Achieve zero water discharge by 2025
- Reduce materials use over the life cycle, for example:
    - Reduce in-plant scrap by 50%
    - Increase material recoverability by X%
    - Increase ability to re-use/re-manufacture/up-cycle/same-cycle
- Reduce energy use intensity over the life cycle, for example:
    - Reduce energy use intensity by X Btu (or kWh)/unit GDP (or unit manufacturing output)
- Reduce GHG emissions over the life cycle, for example:
    - Reduce CO_2 emissions by X /unit GDP
    - Reduce overall CO_2 emissions to X

Examples of Particular Targets

- Eliminate induced seismicity from injected water
    - To less than 4.0
- Make recovery of titanium from additive manufacturing process more effective

Challenges and Barriers

FOCUS QUESTION 2: *What are the key challenges/barriers to improve sustainability in materials, water, and energy management? What are the problems we are trying to solve?*

Table E-2 summarizes participant comments on challenges and barriers to sustainability in materials, water, and energy managements. Workshop participants were asked to vote on the challenges and barriers they perceived as most important. The number of votes received (indicating participants' highest priorities) is shown by asterisks and the vote count is in parentheses.

Table E-2. Challenges and Barriers

Technology and Knowledge

- Need for smart practical technology by integration of optimal designs, industry demands, and finance availability ******(6)
- Lack of deep understanding of sustainability, the interaction of relevant of materials, and water-energy management ******(6)
- Lack of understanding of nexus (energy/water/materials) and ability to apply to technologies
  - Reduce the overall energy use as a system of processes (suppliers, manufacturers, etc.) ***(3)
- Supply/demand integration; integrated energy supply and demand has not been demonstrated
- e.g., require supplier energy reduction
  - Need for incentives for reusable polymeric materials (also need for standards?) **(2)
  - Lack of low cost/energy water treatment technologies *(1)
- In areas of membranes, brine management
- No matured technology, equipment and process for "work integration" for mechanical energy recovery *(1)
- Missing effective methods of solution dehydration in aggressive down-stream chemical processes (drop in) *(1)
- Scalability of technology solutions. Lack of bench scale solutions, have not proven/demonstrated at bench scale. *(1)
- Lack of cost-efficient manufacturing processes to allow for optimized design to minimize material use ******(6)
- Lack of adaptive, reactive technologies ****(4)
- Inability to use components for more than one life cycle ***(3)
- Lack of sensors for monitoring processes**(2)
- Lack of attention to EOL in the design process *(1)

Collaboration

- Benefits/cost of sustainable investments are often spread across supply chain ***(3)
- Lack of visibility into supply chain for decision making (broader impacts) **(2)
- Networking community of different process companies, university labs, etc. (e.g., DOE AMO and DOE Fuel Cell Technologies Office)
- Knowledge and communication barriers across disparate industries
- Integrating diverse stakeholder preferences for long-term goals

Data/Information

- Advanced technology for capturing information of energy, water, materials usage in manufacturing processes for individual industry; lack of data resolution; Internet of everything. **********(10)
- Lack of knowledge about in-facility energy and water end uses (need better tracking)—often only utility meter scale coarseness
- Lack of available information about how by-products can be recycled or re-used (integration of dissimilar industries)
- Lack of data analysis approaches for use of sensor data/information (for smart manufacturing/internet of things) ******(6)
- Lack of expert systems for analyzing processing data ****(4)
- Across industry, there is a disparity in data and associated tools (from those with no/low data and low/no analytical tools to those with very good data and good analytical tools) ****(4)

Table E-2. Challenges and Barriers
• Lack of awareness of materials/water/energy impacts in design-stage decisions ***(3)
Water
• Missing distributed ZLD management of cooling, cutting and washing fluids (avoid dumping) ********(8) • Water issues are moving industry out of the U.S.
Workforce

• Technologies are being scaled for larger manufacturing. Not pushing existing solutions to small manufacturers *(1)
    • Knowledge
    • Economics (ROI)
    • Scale of technology
• Many small and medium enterprises have "Frankenstein" systems that work, though inefficient. No financial or human resources to develop/implement efficient systems.
• Lack of skilled labor/tradespeople *(1)
• Need for more education of school-age kids

Management
• Corporate leadership buy-in (longer term vision) *(1) • By coupling systems, end up with counter-objective outcomes. Increased complexity with interdependent management. • There is a "principal agent problem" with respect to products (i.e., manufacturer may not care about the product's down-stream material/energy/use issues) ****(4) • Heterogeneity of industries and regions (but water is local) ***(3) • There is a lack of connection between manufacturing and opportunities (e.g., recycling) **(2) • Need for improved interconnectivity ("internet of things") • Lack of incentives for new technology implementation • In U.S., 60% of energy wasted, 80% of water wasted, requires a paradigm change • Lack of understanding of near-term opportunities (e.g., wastewater treatment and manufacturing) • Lack of better business case development with proper incentives to carry out goals • Intellectual property issues/corporate charters are an impediment to transparent communication between OEMs, customers, community, and R&D organizations
Cost/Technology Cost

• Technologies to be deployed in industry to reduce energy use (especially significant reductions) require too much capital and/or do not meet typical 1-2 year payback. Economies of scale. ********(8)
• Embedded investment in existing infrastructure
• Incentives (funding); hard to get incentives, don't have good models
• Limited government support in terms of tax credits and guarantees to help drive solving these problems
• Economics: If it is not making money, it is not going to happen!
• ROI/financial
    • Low cost of energy and water
    • High cost of advanced technology
    • Low capital risk tolerance
• Not fully exploring "non-government" funding sources for "sustainable" industry
• Lack of cost effective processes for recycling
• Inefficient pricing ($0 for emissions and near $0 for water) *(1)

Material
• Ineffective materials development pipeline *******(7) • It takes longer to insert material into product than the life cycle of product **(2)

R&D Needs

FOCUS QUESTION 3: *Drawing on the technical challenges identified, what critical R&D is needed to overcome the major challenges to improve sustainability in materials, water, and energy management?*

Table E-3 summarizes discussions on the critical technology R&D that will be required for sustainability in materials, water, and energy management. Workshop participants were asked to vote on the R&D needs they perceived as most important. The number of votes received (indicating participants' highest priorities) is shown by asterisks and the vote count is in parentheses. In the following pages, Figures E-1 through E-6 present an analysis of the highest priority R&D topics for *Materials, Water, and Energy Management*.

Table E-3. R&D Needs
Solutions around ROI ******(8)**

• Early stage techno-economic model
  ◦ Are we funding the right thing?
• Financial planning aspect during start-up phase
• Steady state planning
• Integration of materials, technology development and economics
• Bench scale proof of concept
  ◦ Drop in technology solutions with lower capital expenditures
• Convergence of technologies in materials, energy and water to address what technologies to adopt

Solutions around zero liquid discharge (ZLD) ******(8)**
• Cost effective water treatment • Membranes • Coolants
Solutions around integrated process optimization (financial, demands) ****(6)**
• Identification of integrated processes • Process intensification • Practical technology • Cross domain models and analysis tools, and data for model validation
Solutions around lack of data resolution ********(10)**
• Sensors and activators • Big data analysis tools • Data standards
Solutions around ineffective materials pipeline *****(7)**
• Materials resources are not sustainable • Less expensive materials • Materials/models for closed loop • Less computation, more listening to manufacturing needs • Sustainable material flow analysis
PROCESS Innovation (this category feeds into and is fed by Product Innovation – circular loop)

Table E-3. R&D Needs
• Modular, flexible, distributed manufacturing approaches for sustainable manufacturing ******(6) • Innovative material synthesis technology that reduces water, energy and waste simultaneously ****(4) • Cost effective recovery of spent multi-material finished products **(2) • Industrial waste water treatment technology with a 50% cost reduction (CAPEX and OPEX) *(1) • Circular C-1 utilization (site-specific uses and demonstrations) • Improved waste heat utilization technologies, e.g., thermoelectrics • Technologies for low energy water purification • Reactive separations technologies (e.g., for aqueous separations to reduce energy intensities)
PRODUCT Innovation (this category feeds into and is fed by Process Innovation – circular loop)

• Recycle-friendly alloys (and polymers, inorganics, etc.) ****(4)
• Methods to better utilize/enable use of secondary (post-consumer) materials *****(5)
• Sensors/automation for adaptive, reactive technologies ***(3)
  ◦ e.g., related to material composition and product life cycle
• “Smart” products that provide feedback to sustainable design and manufacturing **(2)
• Bio-based feedstock R&D for sustainably manufactured products *(1)
• “Smart” sensors for process monitoring
• Technology to improve energy management of the “plant floor”, e.g.,
  ◦ Personalized thermal comfort heating/cooling
  ◦ Reliable/ubiquitous occupancy sensing

Data and Analytics
• Develop metrics and functional relationships among water, energy and material attributes (that is, models coupling all of these) ********(8) • System-level approaches that include industrial ecology ****(4) • “Big data” approaches for accessing/analyzing data across the life cycle ***(3)   ◦ How to handle “big data” • Database of materials properties of secondary materials (so designers can utilize these materials) ***(3) • Improved data analytics to provide on-demand feedback for management of systems operations *(1) • Shared data, information, and analysis tools across the supply chain • Address disparities in analytics (and use thereof) for process optimization (across supply chains and sectors) • Collection and analysis of meta-data (nationwide)
Sustainable Manufacturing Design Tools
• Integrated life-cycle design tools and databases with decision-support systems ******(6) • Design tools (from CAD/CAM to process design) that includes sustainability parameters *(1) • Design for disassembly tools and methodologies • Design tools to increase functionality, etc.
Other R&D Needs
• Health impacts of process materials • Incorporate social science research   ◦ What is inhibiting adoption? • Crosscutting training to manufacturing workers to understand energy/water/material nexus • Clarification: Distinction between advanced manufacturing and other manufacturing? Where are we focusing technology needs?

Figure E-1. ZLD: Aqueous & Organic Liquids Conservation & Re-Use

KEY CHALLENGES:
- Recovery limits, input limits
- Fouling resistance-of solutions
- Brine disposal costs (recovery limits) and mechanisms
- Materials compatibility (e.g., corrosion)
- Cost effective treatment technologies (membrane, distillation, crystallization/evaporation, ion exchange, chemical treatment)
- Fluids[4] not designed to be reused/recycled

DESIRED OUTCOMES:
- Integrated demonstration with well documented results
- Fluid and fluid process optimization guidelines for volume minimization
- Increased product recovery
- Brine use value add
- New technology for previously unsolved problems

Fluid Producers | **Fluid Treatments**

R&D Approach

	Fluid producers	Fluid treatments
<3 years	Fluid producers: • Capture industry specifications • Survey best practices • Initial guideline and target metrics for future fluids for reusability	Fluid treatments: • Engage with industrial water treatment OEM and material suppliers • Capture for industry specifications for reuse • Start innovative development and demonstration projects ASAP
>3-5 years	• Producing/piloting/trials of fluids that meet target reusability metrics • Process R&D for fluid minimization	• Piloting/demonstrating of innovative process at source of fluids (industrial site) at an industrially relevant scale (for treatment and reuse)

Performance Goals and Targets

Metrics
- Reduce cost of fluid use and disposal by 50%
- Reduce volume of input fluid and volume disposed by 50%

Potential Participants and Roles

Stakeholders

Industry/Users: Provide required process specifications. Provide test sites.
Industry Technology/Material Developers: Fluid producers. Fluid processing and treatment. Technology development and deployment.
National Labs: Collaborative R&D
Academia: Early stage collaborative R&D and student training
Associations: Dissemination of information. Facilitate relationships.
Collaboration: Sustainable multi-partner industry-university-laboratory research institute to coordinate R&D activities, databases, information and knowledge dissemination. Individual R&D projects with tech developers (SME, labs, institutes). Demonstration programs with tech development and industry partnerships.

Impacts

Saves energy: medium, Energy spent on cooling/heating, cutting and washing fluids
Reduces carbon, wastes, emissions, water: high, Inherent
Accelerates innovation: medium, Produces new technology and approaches
Reduces costs: medium, Could go either way; value proposition may be reduced liability

Improves product quality: low, Should have no impact
Improves competitiveness: medium, May allow process to stay in the U.S.
Increases raw material efficiency / yields: high, Reduce the volume inputs (inherent)

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[4] Fluid includes aqueous, organic and other liquids streams/solutions that are currently disposed of or wasted

Figure E-2. Materials for Sustainable Development

KEY CHALLENGES:	DESIRED OUTCOMES:
• Separation for reuse/recycling • Scarcity and toxicity of clean energy materials • Time to develop and qualify new materials • Knowledge availability for material selection at design simulation • Loss of material performance through use cycles	• New materials and processes to increase reuse by 50% (at equivalent performance) • Improve speed, effectiveness and cost of separation based on new material formulations, or separation processes • Technology for evaluation and optimization of custom material designs • Product design tools that support design for recyclability and separation • Database of properties of sustainable materials (e.g., embodied energy, toxicity, recyclability, etc.) to support selection

R&D Approach

<3 years	• Sustainable material database: open/accessible • Develop product design for separation and recycling toolkit (integrate and enhance existing technologies) • Develop process for removal of coatings and platings from plastic substrates	• Adaptive separation testbed (unit level)
>3-5 years	• New custom plastic blends based on recycled material content • Advanced simulation tools for predicting electrochemical properties of custom materials • Nondestructive measurement of material degradation/performance to support direct reuse • Separation technologies for composite/laminate	• Adaptive flexible remanufacturing and recycling systems

Performance Goals and Targets

Metrics

- Complex engineered (electromechanical) products have 50% material reuse/recycled
- Reduced development cycle time for materials for clean energy products (PV, battery, etc) by 50%
- 25% of plastics support 3x recycle
- 10% of plastics support 4x recycle
- Recycled materials that use polyolefins filled plastics/composites
- 50% replacement of polyolefins with biobased or recycled materials
- New materials for more effective heat exchange in harsh environments—low fouling materials and coatings

Potential Participants and Roles

Stakeholders

Industry/Users. *None stated*
Industry/Material. *None stated*
National Labs: separation test beds *None stated*
Academia. *None stated*
Associations. *None stated*

Impacts

Saves energy: *None stated*
Reduces carbon, wastes, emissions, water: *None stated*
Accelerates innovation: *None stated*
Reduces costs: *None stated*

Improves product quality: *None stated*
Improves competitiveness: *None stated*
Increases raw material efficiency / yields: *None stated*

Figure E-3. ROI: Cost Benefit Analysis to Properly Value Sustainability/Innovation

KEY CHALLENGES:

- High initial capital expense and long payoff
- Lack of technical and economic understanding of integration of materials and natural resources
- Lack of sufficient data and models to validate viability of new integrated technology

DESIRED OUTCOMES:

- Demonstrate drop-in technology that reduces capital expenditure and lessens payback time
- Demonstrate proof of concept (convergence of technologies) at a bench scale
- Gather data from bench scale/pilot scale and model performance from sealed data

R&D Approach

<3 years	Drop-in technology for demonstration: • Create target for reduced capital expenditure and energy use, water usage, payback time • Build bench scale system demonstration with industrial buy-in and defined success metrics	Data/model development and validation: • Collect big data and analysis for cost benefit of integration • Explore technology solutions for down selection—most promising solutions • Link cost benefit analysis with LCA • Develop models from bench scale data and predict future performance
>3-5 years	• Assess progress against targets for scale-up • Build pilot scale system demonstration with private public partnership	• Validate models against pilot data and refine predictive performance

Performance Goals and Targets

Metrics

- Use drop-in technology to demonstrate payback of 3 years and 20% ROI
- Demonstrate reduced water and energy usage by 50% at pilot scale
- Demonstrate x% waste stream utilization from pilot scale
- Industry adopts drop-in technology based on demonstration and validated data/models
- Sustain innovation throughout lifecycle
- Cross-industry adoption from numerous companies

Potential Participants and Roles

Stakeholders

Industry/Users: Reviews, evaluators, approver; fund pilot; early adopters
Industry/Tech Developers: Reviewers, technology selectors, adopters
National Labs: Bench scale developer, pilot scale consultants, consulting
Academia: Workforce development training, continuous basic R&D to feed pipeline, R&D for future innovation
Associations: Inform industry and share successes, vet alternative solutions and get industry to speak with one voice
Collaboration: Multi-partner industry-university-lab collaborative R&D project and later demonstration/deployment assistance efforts (to disseminate database information and encourage continuous collection of data)

Impacts

Saves energy: medium, This method does not disrupt existing facility operations
Reduces carbon, wastes, emissions, water: medium
Accelerates innovation: high, Makes U.S. more competitive, focuses on early industrial adoption
Reduces costs: high

Improves product quality: high
Improves competitiveness: high
Increases raw material efficiency / yields: medium

Figure E-4. Energy, Water, Materials Integrated Process Optimization

KEY CHALLENGES:	DESIRED OUTCOMES:
• Lack of information related to energy, materials, water nexus and usage of each • Need for reduction of variables • Lack of integrated tools • Lack of optimization tools for integration • Need for test bed demonstration tailored tools for industry	• Process and sub-system level sensor networks to capture portable technology • New software tools for manufacturing • Testbed demonstration facility • New engineering companies

Flow Analysis: Integration and Optimization Tools

R&D Approach

<3 years

Flow analysis integration and optimization tools:

- Identify 1 or 2 test beds (facilities/partners)
- Deploy sensor network in testbed that includes ability to swap out subsystems
- Apply data to existing models
- Model validation
- Develop integrated software tools that also include full production costs

>3-5 years

- Deploy to industry to see how much it can achieve
- Make tools user friendly
- Tailor to additional industrial sectors
- Generalize tools beyond test bed

Performance Goals and Targets

Metrics

- Software tool developed for industry
- Practicality of tool used in industry
- Reduce energy, water, materials x% in x years, depending on specific industry

Potential Participants and Roles

Stakeholders

Industry/Users: Industrial partners to provide testbed
Industry/Material: Provide data to test models
National Labs: Contribute to development of tools
Academia: Fundamental methodologies and knowledge of existing models, integrated model development
Associations: Conduct collaborative R&D. Provide avenue to tool deployment.

Collaboration: Multi-partner industry, university, lab and demonstration facility

Impacts

Saves energy: high
Reduces carbon, wastes, emissions, water: high
Accelerates innovation: medium
Reduces costs: medium
Improves product quality: medium
Improves competitiveness: high
Increases raw material efficiency / yields: high

Figure E-5. Innovative Processes and Products

KEY CHALLENGES:	DESIRED OUTCOMES:
• Lack of cost effective sustainable manufacturing processes • Lack of, and the disparity across, the manufacturing sector and supply chains • Lack of understanding of the nexus between energy, water, and materials	• Significantly improve, via sustainable manufacturing, water, energy, carbon and materials use intensity in the U.S. • Fully integrated manufacturing ecosystem • Competitive advantage to manufacture innovative products and processes (based on sustainable and clean energy technology)

	Develop Sustainable Manufacturing Processes	Develop Sustainable Products
R&D Approach		
<3 years	• Roadmap modular, flexible, distributed manufacturing approaches • Develop metrics and functional relationships for water, energy, and materials • Build a database of material properties of secondary materials	• Begin to develop recycle friendly alloys and other materials • Investigate technologies that can increase recycling rate • Develop techniques that can enhance identification of materials (markers, tags, etc)
>3-5 years	• Develop integrated life cycle design tools and databases • Develop innovative material synthesis technology that reduces water, energy, and waste simultaneously	• Incorporate recycle friendly alloys in products • Test and demonstrate recycling technologies • Implement disassembly technologies
Performance Goals and Targets		
Metrics	• Technologies that can achieve an order of magnitude reduction in water, energy, carbon, and/or use intensity that can lead to a1% or greater impact on overall U.S. energy use	• Increase the amount of products that can be recycled by a factor of 2 within 10 years • Increase the lifespan of the product

Potential Participants and Roles

Stakeholders

Industry/Users: Best practices, cost sharing
Industry/Material: Technical advice and support and collaborative R&D
National Labs: Tech transfer, development, and scale up
Academia: Tech transfer, development and scale up and workforce development
Associations: Roadmapping and working groups
Other: Develop product specifications and standards (e.g., ISO)

Impacts

Saves energy: high
Reduces carbon, wastes, emissions, water : high
Accelerates innovation: high
Reduces costs: –

Improves product quality: medium - Increase use intensity should yield improved quality
Improves competitiveness: high
Increases raw material efficiency / yields: high

Figure E-6. Design Concepts and Tools for Sustainable Manufacturing

KEY CHALLENGES:	DESIRED OUTCOMES:
• Existing design concepts are not broad enough for sustainable manufacturing o Collect data for design concept develops/sustainable manufacturing o Sustainable capabilities then need to be incorporated into design	• Design concepts for sustainability; sustainable products mostly data for design concepts/sustainability manufacture • Implementation of design tools/manufacturing; make company more sustainable and profitable; increase number of jobs

R&D Approach

<3 years

- Capture available sustainable design and production design concepts for various metal processes
- Create data/database and fill capability gaps for concept development and R&D
- Create output system for sustainable design concepts and production (Beta version)

>3-5 years

- Refine Beta version of sustainable design and production
- Validate Beta version
- Expand and extrapolate to other sectors

Performance Goals and Targets

Metrics

- Better design tools/concepts for sustainable products
- Better design tools for sustainable processes
- Metals: 10% reduction in water use, 50% in-plant recycling, 30% longer product life

Potential Participants and Roles

Stakeholders

Industry/Users: Supply sustainable design data and progress, conduct collaborative R&D
Industry/Material: Beta tester for sustainable concepts
National Labs: Create sustainable design concepts, help with validation
Academia: Provide sustainable design tools and sustainable processes; collaborative R&D on design concepts
Associations: Facilitate communications and help implement

Impacts

Saves energy: medium - Ability to design for sustainability
Reduces carbon, wastes, emissions, water : medium - Ability to design for sustainability
Accelerates innovation: high – Expedite for product and process development
Reduces costs: medium
Improves product quality: high - Reducing life-cycle analysis effects
Improves competitiveness: high - Improves life cycle analysis effects
Increases raw material efficiency / yields: high - Sustainable process
Other: high - Improves system knowledge

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