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Acronyms and Definitions

AI	Artificial Intelligence
Al	Aluminum
BMS	Battery management system
CE	Circular Economy
c-Si	Crystalline silicon photovoltaic modules
CdTe	Cadmium-Telluride photovoltaic modules
CIGS	Copper–indium–gallium–(di)selenide photovoltaic modules
Co	Cobalt
CRM	Critical Raw Materials
DfR	Design for Recycling
DoE	Department of Energy
EoL	End of Life
EPEAT	Electronic Product Environmental Assessment Tool
EV	Electric Vehicle
E-Waste	Electronic Waste: discarded products with a battery or plug
FAIR	Findable, Accessible, Interoperable, Reusable
GHG	Greenhouse Gas
GW	Gigawatt
IoT	Internet-of-Things
IP	Intellectual Property
LCA	Life Cycle Analysis
Li	Lithium
LCO	Lithium-cobalt-oxide
LIB	Lithium-Ion Battery
Mg	Magnesium
MML	Material Measurement Laboratory
Mn	Manganese
Nd-Fe-B	Neodymium-Iron-Boron magnets
Ni	Nickel
NiMH	Nickel-Metal Hydride Battery
Mt	Million Metric Tons

NIST	National Institute of Standards and Technology
NREL	National Renewable Energy Laboratory
OEM	Original equipment manufacturer
Pb-acid	Lead Acid Battery
PC	Personal Computer
PV	Solar Photovoltaic
R&D	Research and Development
REE	Rare Earth Elements
TEA	Techno-economic Analysis

Executive Summary

The National Institute of Standards and Technology (NIST) held a Technical Workshop on January 27 and 28, 2021 to assess the state and challenges of a Circular Economy (CE) in the High-Tech World. Scientists, researchers, and program managers in the CE arena, from industry, academia, government, national laboratories, and non-governmental organizations gathered virtually to identify challenges and key priorities to facilitate the reuse, repair, and recycling of electronic products, solar panels, and batteries. The results of the workshop provide important input for program planning and research directions that can advance materials design, use, reuse, and recovery, thus enhancing circularity.

Consumer demand, the internet of things (IoT), and recent legislative and policy activities aimed at addressing climate change have increased demand for renewable energy, electric vehicles (EV), and electronic devices. Already, electronic waste is the fastest growing sector of the solid waste stream, and projections estimate a steep rise in end-of-life (EoL) solar panels and EV batteries in the coming decades. Further, these high-tech products are increasingly designed to be faster, lighter, smaller, stronger, more functional, more integrated, and more durable than previous generations due to the application of increasingly sophisticated material components and design parameters. Traditionally, materials have followed a largely linear path – extraction, production, distribution, consumption/use, disposal – but interest in environmental and social impacts as well as supply chain security has spurred a transition to a more CE.

This workshop aimed to better understand the technical and economic barriers inhibiting CE of electronic products, solar panels, and batteries; identify research and development (R&D) priority areas needed to overcome those challenges; and define NIST's role(s) in CE.

The workshop covered five main topic areas: 1) how do we create a CE?; 2) recycling challenges for electronics, batteries, and solar panels; 3) boundary-spanning tools to support CE; 4) reuse, repair, and refurbishment in CE; and 5) best practices for CE.

Overarching challenges and needs, several of which crosscut multiple sessions and breakout groups, emerged from the workshop. They include the following:

- Product Evolution: Computers and electronic components are proliferating in products such as washing machines, thermostats, etc., while simultaneously the embedded devices contain decreasing amounts of high-value materials such as precious metals and rare earth elements (REE). Furthermore, designers of high-tech products prioritize functionality, performance, and cost with little regard for repair, refurbishment, or recycling (i.e., design for recycling, DfR). As a result, while the growing application of electronics provides a massive opportunity for CE practitioners, the constant evolution of products, form factors, assemblies, and material compositions may inhibit economic recovery and recycling.

  This challenge can be alleviated through the following: increased standardization across product types and form factors, information sharing regarding device/component provenance, composition, and material content, and increased participation between manufacturers and recyclers during the product design phase.

- CE Metrics, Frameworks, and Tools: Multiple frameworks and system-level assessment tools have been developed utilizing a diverse range of metrics to evaluate sustainability performance (e.g., social, environmental, and economic impacts) of high-tech products or materials therein. Examples include life-cycle assessment (LCA), techno-economic analysis (TEA), material flow analysis, and risk modeling frameworks of critical mineral commodities. To date, these tools have largely focused on materials and material loops and are often based on outdated or incomplete data.

The advancement of CE frameworks and tools should consider the following: characterization of the interconnectivity between product systems; energy tracking and correlated environmental impacts; the analysis of sustainability across system levels (product levels to macro economy levels); and the integration of LCA and TEA to model reuse, repair, and recycling technologies and processes to aid EoL decision-making. Data needs in this area include material stocks and flows (e.g., cobalt); product level sales, lifespan, and EoL generation estimates; recycling operations, processes, and outputs (e.g., assay results); as well as data to support EoL decision-making such as statistical risk data, malfunction rates and causes, and reuse market potential.

- Infrastructure and Workforce: Infrastructure to support a CE for high-tech products is limited in the U.S. Collection and transport of high-tech products at EoL poses a challenge due to consumer confusion regarding how/where to recycle unwanted equipment, data security concerns, and the disposal of hazardous and combustible materials and components (e.g., lithium-ion batteries). The typical recycling process of electronic scrap involves battery removal (if present), followed by shredding to separate glass, steel, plastic, aluminum, and copper. Similarly, most PV recycling is bulk recycling to recover aluminum, cables, and glass. Less than 1 % of REE are recovered from electronic equipment. Furthermore, the shredding process produces recovered materials (after separation) of poor quality and low value.

  Collection systems can be improved through increased consumer education as well as retail or manufacturer take-back programs funded through means such as an extended producer responsibility (EPR) regulation. Recycling infrastructure needs to be adaptable to the evolution of products and form factors which requires data and information about equipment design (e.g., material/chemical composition). Recovery of semiconductor and other metals necessitates a switch to high-value recycling using focused extraction and/or chemical methodologies. Such technologies exist for certain applications (e.g., recovery of metals from Si cells), but are currently uneconomical. Additionally, R&D is needed to recover high-purity silicon and glass back into the supply chain, as opposed to down-cycling applications.

  While automation and the use of robotics is increasing in some CE sectors, many are reliant on the continued use of manual labor. Such labor is required for disassembly, including battery removal for recycling, as well as assessment for value in parts or units and testing for reuse. Skilled labor is in short supply due to competition from other manufacturing sectors. Education and training programs ranging from K-12 repair/refurbishment programs to apprenticeship programs would be useful to support the CE workforce.

Potential NIST Action Items:

- Data and databases: NIST can bridge the following data gaps: material and component specifications of new products to bridge the gap between manufacturing and recycling; distribution of CE infrastructure including locations and processes associated with collection, reuse, repair, refurbishment, and recycling; material and product stocks and flows in the economy; performance and financial data to support reuse and repair (particularly for batteries); as well as a materials marketplace or "clearing house" of quality controlled (QC'd) materials or products. In addition, NIST can develop comprehensive data repositories from the myriad databases that already exist.

- Standards: Standardization is needed to support consistency and reliability in the CE. Examples of standards NIST could develop include the following: Product design; performance metrics for reuse/repaired products; information standards for supply chains, recycled materials QC, best practice guides (e.g., data wiping/erasure, assembly/disassembly), expected lifetime certification, battery transport, discharge, and safety.

- R&D: Examples of research that NIST can perform include: Purity tolerances for post-consumer feedstocks; rapid material composition fingerprinting; publicity of product materials/composition, while protecting IP; materials science for the reduction/replacement of rare materials; develop analytical methodologies and appropriate standard reference materials (SRMs) for the composition of recycled materials; development of protocol for assessing the state of spent batteries; blockchain as distributed ledger for tracing material content; application of AI and robotics to identify, assess, and/or disassemble devices; neutron activation analysis for detection of rare earth elements; and high-value materials recovery (e.g., critical metals, solar grade silicon).

- Education/Outreach and Training: NIST can support the CE by providing education and guidelines on topics such as data wiping/erasure, best practices for reuse and recycling, as well as publicizing a repairability index to rate new products on their ability to be repaired. NIST can also support the CE workforce through K-12 educational programs, apprenticeships, and training programs

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1 Background and Motivation

Electronic devices are proliferating globally, both through the continued generation of existing products (e.g., mobile devices, computers, televisions) as well as the expansion into new product categories such as washing machines, thermostats, clothing and wearable accessories, and automobiles (i.e., the internet of things, IoT). Additionally, consumer demand as well as recent legislative and policy activities have increased production of renewable energy technologies and electric vehicles (EVs). For example, President Biden signed Executive Order 14008: "Tackling the Climate Crisis at Home and Abroad", on January 27, 2021, committing to increase renewable energy production in the U.S. and convert all federal, state, local and tribal vehicle fleets to "clean and zero-emission vehicles." State and local governments are also implementing climate change policies and programs, incentivizing renewable energy projects and vehicle electrification [1, 2, 3].

The proliferation of electronics, solar panels, and batteries creates the increased generation of obsolete products. Electronic waste (e-waste – discarded products with a battery or plug) already constitutes the fastest growing sector of the solid waste stream, both in the US and globally, and projections estimate this trend to continue [4]. United Nations University (UNU) researchers estimate that 53 million metric tons (Mt) of e-waste was generated globally in 2019, up 21 % in just five years [4]. Americans alone create nearly 7 Mt of e-waste annually, an average of roughly 46 pounds per capita per year [5, 6]. Currently, a mere 15 % of e-waste generated in the U.S. is collected for recycling [6].

Global installed solar photovoltaic (PV) capacity grew from 1.4 gigawatts (GW) in 2000 to 512 GW in 2018 and is expected to reach 4500 GW by 2050 [7, 8]. Considering an average panel lifetime of 30 years, the cumulative mass of global PV waste is estimated to reach 8 Mt in 2030 and 80 Mt by 2050, averaging 6 Mt per year by 2050 [9]. The U.S. alone is estimated to generate a cumulated 10 Mt of PV waste by 2050, second only to China [7]. Crystalline silicon (c-Si) modules currently represent more than 90 % of the global PV market, however, competing cell technologies such as those using thin films (e.g., cadmium telluride, gallium arsenide, copper indium gallium selenide) may change the waste stream composition in the future [7].

Batteries are increasingly used for stationary energy storage as well as large- and small-format mobile applications. Lithium-ion batteries (LIB) are in particularly high demand compared to other battery types (e.g., NiMH and Pb-acid) due to their higher voltage output, longer lifespan, better resistance to self-discharge, higher resistance to elevated temperatures, compact design, and lower environmental risks [10]. In the U.S. alone, 46 million passenger electric vehicles (EVs) are anticipated to be on the roads by 2035 [11]. Thus, the application of EV LIBs is expected to increase from 250 gigawatt-hours in 2020 to more than 1,700 gigawatt-hours in 2030 and 5,000 gigawatt-hours in 2050 [12]. LIB production estimates have posed concern regarding resource availability and price increases of lithium and transition metal elements including cobalt, nickel, and manganese [13, 14]. EV batteries are expected to last about 10 years for propulsion and possibly another 5-10 years in secondary applications such as small-format mobility (e.g. scooters, wheelchairs) or stationary utility grid storage [13]. Market analysts estimated that 500,000 tons of batteries reached end of life (EoL) in 2020 and will rise to 1.2 million tons in 2025 and 3.5 million tons in 2030, a seven-fold increase [12].

The material composition of electronics, solar panels, and batteries are increasingly complex. Up to 69 elements from the period table can be found in electronics (Figure 1), including precious metals and critical raw materials [15]. While often used interchangeably, the terms "rare earth", "critical", and "precious" as they refer to mineral elements mean different things. Rare earth elements (REEs) are actually not the rarest in the Earth's crust (but usually not concentrated in mines), but rather are considered critical due to their use in many technologies and potential geopolitical supply disruptions [16]. Precious metals are generally the rarest elements in the Earth's crust and are also considered critical given their use in technology and limited availability [16]. Critical minerals are generally identified by national governments (e.g., U.S. Department of Interior [17], European Commission [18]) based on their importance to the economy and national security [19].

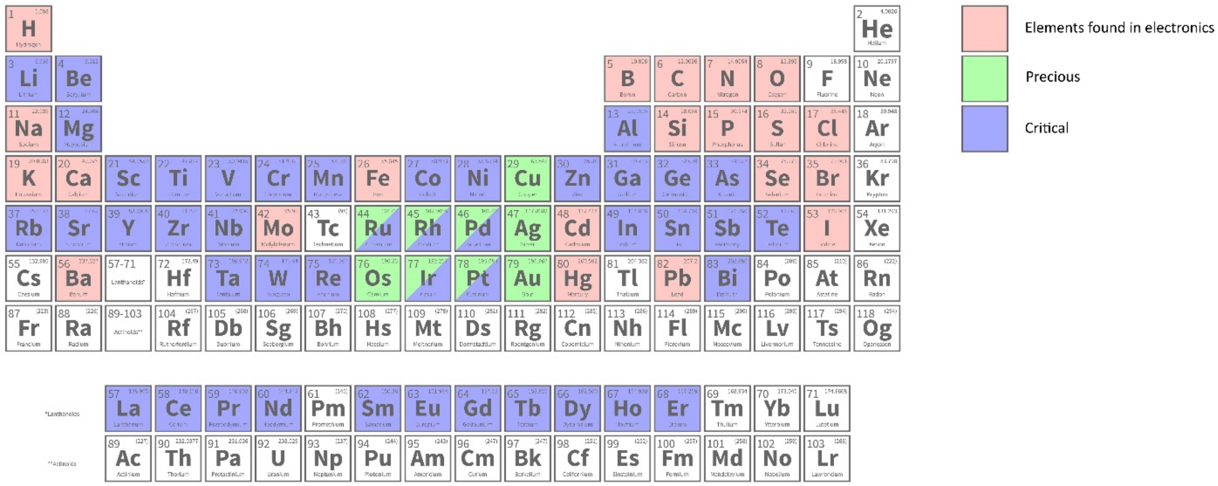

Figure 1: Elements used in electronic products, highlighting precious and critical materials [15, 17]

On a mass basis, electronics are primarily comprised of ferrous and non-ferrous metals, plastic, and glass, while the precious and critical material content makes up a small fraction (Table 1). Similarly, solar panels and batteries contain an intricate mix of material components, many of which require high purity (e.g., solar grade silicon is at least 6N, or 99.9999 % pure) [7]. Most materials used in LIBs are neither rare earth nor precious metals, although they are critical due to their economic importance and national security. For example, more than half of global lithium and cobalt production is consumed by batteries [16]. That said, cobalt has been identified as an element of concern in the production of LIBs due to diminished reserves predicted with the cumulative world demand for batteries coupled with concerns about child labor in the Democratic Republic of the Congo where most cobalt is mined [13]. This concern has driven EV battery manufacturers to adjust chemical formulations to rely less on cobalt and more on nickel.

Table 1: Material Composition of High-Tech Products (content %wt/wt) (Sources: [15, 20, 21, 16, 22, 23, 24])

Electronics (%)		Solar Panels (typical c-Si module), (%)		Batteries (typical LIB LCO cathode), (%)	
Metals	28-60	Glass	76	LCO Cathode:	36
Iron and Steel	8-50	Plastic	10	Lithium	7
Non-ferrous:	1-13	Aluminum	8	Cobalt	60
Aluminum	0.8-4.7	Silicon	5	Oxygen	33
Copper	13-35	Copper	1	Graphite	19
Nickel	0.002-2.6	Other metals: (silver, tin, lead)	<0.1	Copper	16
Zinc	0.2-8.2			Aluminum	8
Lead	1-4.2	CdTe and CIGS panels include other metals: (e.g., nickel, zinc, gallium, indium, germanium, cadmium, telluride, selenium)	<1	Electrolyte:	
Gold	0.008-0.1			$LiPF_6$	2
Silver	0.20-0.33			EC	6
Plastics	20.6-23			DMC	6
Flame retardant	5			Carbon black	2
Non-flame	15			Binder (PVDF)	3
retardant	2-33			Plastics	2
Glass and Ceramic	2.6				
Wood	0.90				
Rubber					

LCO: Lithium cobalt oxide; $LiPF_6$: Lithium salt; EC: Ethylene carbonate (solvent); DMC: Dimethyl

The increased production of high-tech products, combined with the material value within, represents a huge opportunity for recovery. The material value of e-waste alone is estimated at $62.5 billion USD, three times more than the annual output of the world's silver mines [25]. Certain metals such as gold used in cell phones and PCs have a relatively high level of concentration (e.g., 280 grams per ton of e-waste), roughly 100 times higher than that of gold ore [15, 25]. Furthermore, harvesting the resources from EoL products produces substantially less carbon emissions than extraction from the Earth's crust. That said, working products and components are worth more than the materials they contain and thus extending the life of products through reuse, repair, and refurbishment brings an even greater economic as well as environmental benefit.

Unfortunately, the traditional life of high-tech products has followed a largely linear path – material extraction, manufacture, distribution, consumption/use, disposal. But increased awareness and interest in environmental and social impacts of products as well as supply chain security concerns and associated economic impacts have spurred a transition to a more circular economy (CE) in which products, components, and materials are continuously valued and re-used, i.e., maintained in the economy.

Progress is being made in the transition to a CE for high-tech products, but many challenges persist. To better understand the technical and economic barriers inhibiting a CE for electronics, solar panels, and batteries, the National Institute of Standards and Technology (NIST) held this virtual workshop to identify R&D priority areas and needs for data, measurement, and standards to facilitate a CE.

Workshop Overview

To better understand the needs to overcome key challenges and NIST's role in this area, NIST held a virtual workshop on January 27 and 28, 2020 entitled *Circular Economy in the High-Tech World*. Representatives from industry, academia, government, trade associations, national laboratories, and non-governmental organizations gathered virtually to hear presentations from industry, academia, nonprofits, and NIST program managers, and participate in topical breakout sessions. Discussion topics focused on identifying key challenges to high-tech reuse, repair, refurbishment, and recycling and priority needs in addressing barriers.

Transitioning to a CE is essential to reduce U.S. reliance on imports of certain mineral commodities that are vital to the Nation's security and economic prosperity. As global production of high-tech products intensifies, the U.S. recovery and recycling ecosystem must raise its performance. By sharing priorities and ideas, industry, academia, nonprofit, and government partners can more effectively unite to facilitate a CE.

About the Workshop Coordinating Office

For NIST, the definition of a circular economy is an economy which aims to keep atoms and molecules cycling within the economy and out of unwanted sinks (e.g., land, air, and water systems). This necessitates a transition away from the current linear economic model toward a regenerative model based on principles of material circularity and designing out waste and pollution. A circular economy therefore entails extending the life of products and materials for as long as possible. This is performed through design for durability, reuse, repair, and remanufacturing, as well as recovering materials at end-of-life through recycling. A circular economic model also mitigates many of the risks posed by resource depletion, unmanaged disposal, adverse environmental impacts, and social and environmental injustice while creating value and new business opportunities.

NIST has expertise in several areas that will contribute toward this field, including materials, chemical and biological sciences, reference material development, sorting and identification technologies, data repositories and support for data standards, and life cycle assessment tools. While other Federal partners are investing in this area, NIST is uniquely poised to provide the measurement and standards capabilities that are needed to promote widespread adoption of the technologies developed. Additionally, the US has the capability to create a robust circular economy, but lacks any unified infrastructure for collecting, sorting, identifying, and transporting waste streams. NIST can address these areas with appropriate attention to stakeholder engagement to understand community needs through workshops as well as program alignment with critical partners.

This workshop report summarizes the presentations and breakout group discussions that took place at this event. Note that the results presented here are a snapshot of the viewpoints of the experts who attended the workshop; they do not necessarily reflect the views of the broader materials development community.

Workshop Process and Sessions

The workshop took place over two-days each of which consisted of a plenary presentation in the morning, followed by topic-specific sessions. Plenary presentations featured invited experts from relevant industry and academic programs and helped to explain the need for a CE for high-tech products as well as identify limits to circularity. The subsequent sessions focused on key topics relevant to transitioning to a CE and ranged from a systems-level perspective to specific industry challenges. **Detailed session content is provided in Appendix C, and is summarized as follows:**

Session 1: How do we Create a Circular Economy?

Speakers: Maria Curry-Nkansah, National Renewable Energy Laboratory (NREL)
Nik Engineer, Ellen MacArthur Foundation (EMF)
Alessandra Hool, Entwicklungsfonds Seltene Metalle (ESM) Foundation
Gregory Keoleian, University of Michigan
Nedal Nassar, U.S. Geological Survey

The main goal of this session was to identify system-wide barriers to a CE and how to overcome them. Five experts were invited to each speak for 15 minutes on this topic. The experts discussed CE efforts in their organizations, systemic barriers to transitioning to a CE, as well as data, metrics, models, and analytical tools developed to assess and propel a CE. Speakers identified specific materials used in high-tech products which are at risk of experiencing supply challenges, whether due to resource scarcity, geopolitical constraints, or coupled extraction as byproduct elements. Speakers also provided examples of a CE in practice for select products and materials.

Session 2

Session 2 was comprised of three simultaneous sub-sessions focused on recycling challenges for electronics, batteries, and solar panels. Each session included a panel of five or six topical experts from industry, national laboratories, and academia. Each panelist spoke for five minutes to introduce their organization, their role in recycling, as well as to mention a key challenge from their perspective. Following the panelists' introductions, they answered questions from the audience and facilitators. The last portion of the session included facilitated breakout sessions using the Slido app.

Session 2a: Recycling Challenges for Electronics

Panelists: Julie Daugherty, Multimetco, Inc.
George Lucas, Gannon & Scott
Julie Schoenung, University of California, Irvine
John Shegarian, Electronics Recyclers International (ERI)
Peter Afiuny, Urban Mining Company

The goal of this panel sub-session was to identify technical and economic challenges and needs specific to the recycling of electronic products. Panelists included recycling practitioners and metals reclaimers, as well as an academic researcher. The panelists opened the session by discussing their role in electronics recycling and a key challenge from their perspective. Subsequent discussion and Q&A touched on the growth of the e-waste recycling industry, current practices in material recovery via e-waste recycling and material recovery, the changing volume and composition of the waste stream, as well as needs and necessary adaptations to recover electronic products, components, and materials more economically.

Following the panel discussion and Q&A, workshop attendees participated in a breakout discussion facilitated by Zachary Trautt, from the Material Measurement Laboratory at NIST. Dr. Trautt used the Slido survey and polling application to engage attendees in questions related to challenges and needs for advancing electronics recycling. The questions included multiple choice, word cloud, and "ideas," in which respondents could provide text responses and others could 'up vote' and 'down vote' the response or add additional comments (see Appendix D for Slido questions and responses from all Session 2 breakouts).

Session 2b: Recycling Challenges for Batteries

Panelists: Callie Babbitt, Rochester Institute of Technology
Todd Coy, Kinsbursky Brothers, Intl.
Linda Gaines, Argonne National Lab
Jean-Christophe, Lambert, Lithion Recycling
Stephanie Shaw, Electric Power Research Institute (EPRI)

The goal of this panel session was to identify technical and economic challenges and needs specific to battery recycling. The panelists included battery recycling practitioners, national and academic researchers, as well as a nonprofit research and development organization. The panelists opened the session by discussing their role in battery recycling and a key challenge from their perspective. Further discussion and Q&A touched on issues associated with battery safety during transport and processing, challenges associated with different battery form factors and chemistries, different recycling processes, identifying and certifying batteries for reuse versus recycling, logistical and economic challenges of collection, sorting, and recycling, as well as the changing role of recyclers in the waste management sector.

Following the panel discussion and Q&A, workshop attendees participated in a breakout discussion facilitated by John Bonevich of the Material Measurement Laboratory at NIST. Dr. Bonevich used the Slido survey and polling application to engage attendees in questions related to challenges and needs for advancing battery recycling. The questions included multiple choice, word cloud, and “ideas,” in which respondents could provide text responses and others could ‘up vote’ and ‘down vote’ the response or add additional comments.

Session 2c: Recycling Challenges for Solar Panels

Panelists: Evelyn Butler, Solar Energy Industries Association (SEIA)
Garvin Heath, NREL
Cara Libby, EPRI
Parikhit (Ricky) Sinha, First Solar
Meng Tao, Arizona State University
Kristina Whitney, Recycle PV Solar

The goal of this panel sub-session was to identify technical and economic challenges and needs specific to solar panel recycling. The panelists included solar panel recycling practitioners, national laboratory and academic researchers, an industry association representative, as well as a nonprofit research and development organization. The panelists opened the session by discussing their role in solar panel recycling and a key challenge from their perspective. Further discussion and Q&A touched on issues such as challenges to recovering high-value materials from solar panels, the projected growth of the solar panel waste stream, panel design changes and their effects on dematerialization, current and future recycling processes and technologies, and economic challenges of solar panel recycling.

Following the panel discussion and Q&A, workshop attendees participated in a breakout discussion facilitated by John Perkins of the Material Measurement Laboratory at NIST. Dr. Perkins used the Slido survey and polling application to engage attendees in questions related to challenges and needs for advancing solar panel recycling. The questions included multiple choice, word cloud, and “ideas,” in which respondents could provide text responses and others could ‘up vote’ and ‘down vote’ the response or add additional comments.

Session 3: Boundary-Spanning Tools to Support a Circular Economy

Speakers: Melissa Bilec, University of Pittsburg
Alberta Carpenter, NREL
John Glaser, U.S. Environmental Protection Agency (EPA)
Carol Handwerker, Purdue University

The goal of this session was to present and discuss existing and necessary tools that cross disciplinary bounds to support a CE. Speakers from academia, the U.S. government, and a national lab each spoke for 15 minutes discussing frameworks and tools developed to measure, model, and evaluate transitions to a CE. These tools are designed to better understand and assess interactions between resources systems and actors, measure and model system dynamics and impacts (e.g., environmental, social, economic), and ultimately aid decision-making for consumers, policymakers, and practitioners.

Session 4: Reuse, Repair, and Refurbishment in a Circular Economy

Speakers: Josh Lepawsky, Memorial University
Eric Lundgren, Big Battery
Nabil Nasr, The REMADE Institute
Adam Shine, Sunnking
Kyle Weins, iFixit

The goal of this session was to discuss challenges facing reuse, repair, and refurbishment of electronics, batteries, and solar panels. Speakers represented reuse and repair practitioners, academia, and a refurbishment research institute. They each spoke for 15 minutes about their role and challenges in this sector of the CE. While all high-tech products were up for discussion, the practice of reuse, repair, and refurbishment is currently largely focused on electronics and batteries (EV LIBs). Life extension of solar panels is less important due to their long lifetime, lack of moving parts or components, and increased efficiency of new modules. Speakers discussed issues such as the role of reuse and repair in the CE, challenges for repair due to product design, repairability standards and right to repair legislation, as well as the role of manual labor in reuse and repair.

Session 5: Best Practices for a Circular Economy

Speakers: Adina Renee Adler, Institute of Scrap Recycling Industries (ISRI)
Mark Buckley, One Boat Collaborative
Corey Dehmey, Sustainable Electronics Recycling International (SERI)
Kathleen Fiehrer, Intel
Joanne Larson, Seagate

The goal of this session was to discuss the roles of government and industry in the transition to a CE and to present case studies of the CE in high-tech industries. Speakers represented an industry trade association, a sustainable electronics certification organization, as well as three companies: two technology manufacturers and one sustainable business consultant. Each speaker presented for 15 minutes, and discussed the responsibilities of government and industry and, the role of standards and certification programs, as well as best practices regarding product procurement, waste diversion, and circularity within a product supply chain.

Session 6: Breakout Session

The final session of the workshop included a facilitated breakout discussion hosted by Kelsea Schumacher of the Circular Economy program at NIST and Martin L. Green of the Materials Measurement Science Division at NIST. Drs. Schumacher and Green used the Slido application to engage participation through multiple choice, world cloud, and open-ended questions. The questions were grouped into four themes: enabling a CE, design, use/reuse, and end-of-life (EoL) management and asked about specific challenges and needs in each category as well as specific action items NIST might perform. Slido questions and responses can be found in Appendix D. Following the Slido questions, Drs. Schumacher and Green invited attendees to participate in an open discussion about all of the workshop topics and how NIST can enable a transition to a CE.

2 Workshop Outcomes

During the workshop introduction, participants were asked using a Slido word-cloud poll to identify a major challenge to a CE for high-tech products. The resulting word-cloud is presented in Figure 2 where the larger and brighter-colored words represent those inserted by multiple participants. Therefore, challenges related to economics, complexity, infrastructure, and technical processing were identified most frequently as key barriers to circularity.

Figure 2: Slido word cloud derived from participant response to major challenge to a CE for high-tech products

This section provides the key findings from the workshop presentations and breakout sessions (summarized in Appendices C and D). It is organized as CE barriers and needs.

2.1 Barriers to a Circular Economy

Several barriers were brought to light throughout the workshop presentations, discussions, and Slido responses. Many of these cut across different sectors of the CE, and pertain to all product categories (electronics, batteries, and solar panels). Other barriers are specific to reuse, repair, and manufacturing, and many are product specific. This session outlines the challenges for each of these areas.

Cross-Sector Challenges

A CE for high-tech products is challenged by limited publicly available data and information. Systems to support recovery, reuse, and recycling are particularly hindered by the lack available data specific to materials, products, infrastructure, and markets. Another major problem is inconsistent nomenclature related to CE issues across sectors and industries. Without standardization of terms, cross-sectoral data cannot be combined or analyzed, thus inhibiting the practices and system development necessary for a CE.

Multiple frameworks and system-level assessment tools have been developed utilizing a diverse range of metrics to evaluate sustainability performance (i.e., social, environmental, and economic impacts) of high-tech products or materials therein. Life-cycle assessment (LCA), techno-economic analysis (TEA), material flow analysis (MFA), and risk modeling frameworks are all examples of such tools. To date, these tools have largely focused on materials and material loops and are often based on outdated or incomplete data. For example, speakers in Session 1 stated their inability to effectively model mineral stocks and flows (e.g., cobalt) due to the lack of data available. Similarly, gaps in product level data restrict the flow modeling of electronics in the U.S. EPA's ADEPT tool. Increased development and coordination between the frameworks and tools are necessary to effectively model system dynamics. They must also be included in design processes to enable the inclusion of sustainability factors in conjunction with functionality and performance.

The dilution factor is a key challenge facing EoL recovery and recycling of high-tech products. While the total generation of electronics, batteries, and solar panels is rapidly increasing, products contain progressively lower concentrations of high-value materials (e.g., precious and critical metals). The result is that smaller amounts of valuable materials are increasingly distributed globally, and therefore recovery becomes more challenging and expensive.

Product design is currently another barrier to a CE but needs to be part of the solution. Design plays a major role in the lifecycle and EoL recovery of electronic devices, batteries, and solar panels. Current products are designed for functionality and performance, with little consideration for reuse, repair, or recycling. When components and equipment are bonded in place, as is current practice, disassembly and separation is very difficult, if not impossible. This hinders equipment and component reuse and repair. Further, while some equipment can be put in a shredder whole, battery-powered equipment must be disassembled to remove the battery prior to shredding. This practice is extremely labor and time intensive when parts and components are glued together.

Infrastructure to support a CE for electronics, batteries, and solar panels is limited in the U.S. Collection of high-tech products at EoL is challenged due to consumer confusion regarding how and where to recycle unwanted equipment, as well as concerns about data security and destruction. Collection of EoL solar panels is hindered by the lack of recovery infrastructure, whereas battery collection and transport are challenged by safety concerns due to potential LIB ignition. Further, conventional recycling of high-tech products involves bulk recovery through a shredding model. While this practice recovers high-content materials such as glass, aluminum, steel, and copper, it fails to recover high-value materials such as precious and critical metals (i.e., materials with greatest supply chain concern), or high-grade materials of the purity necessary for reintroduction back into high-tech supply chains (e.g., solar grade silicon).

A trained, experienced workforce is another barrier to a CE for high-tech products. While automation and the use of robotics is increasing in some sectors of the CE, many are reliant on the continued use of manual labor. Such labor is required for electronics disassembly, including battery removal for recycling, as well as assessment for value in parts or units and testing for reuse. Manual labor is also necessary for battery identification, assessment, disassembly, and material recovery. Additionally, reclaimers and refiners need skilled operators to run thermal reduction, melting, and chemical processing equipment, as well as perform laboratory analysis and assaying. However, skilled labor is in short supply due to competition from other manufacturing sectors, exposure to hazardous materials, as well as lack of educational and training programs focused on this sector.

Reuse/Repair/Refurbishment Challenges

Products entering the market are increasingly more highly integrated, complex, and smaller, and therefore more difficult to disassemble and repair or refurbish. Product components are often glued in place and assemblies bonded together, rendering rapid disassembly challenging, if not impossible. In addition, each year new products and models are introduced, which repair and refurbishing operators must reverse engineer to understand and fix. Specific product information necessary for repair, as well as service manuals, parts, and tools are often considered proprietary by manufacturers and is therefore not available. Many electronics manufacturers have instituted their own systems for repair, whereby the only means to fix equipment or obtain parts is through the OEM or their authorized vendors. Right-to-repair legislation is intended to address this, allowing consumers the ability to repair or modify electronic equipment and making available the product information, parts, and tools necessary for repair.

Standardization of products is another barrier for reuse and repair, especially for batteries. Different form factors, chemistries, and compositions make battery reuse and recovery difficult. For example, Mr. Lundgren from Big Battery brings in LIBs from EVs and repurposes them to power new products. However, his ability to reuse batteries in second life applications would be significantly increased if EV batteries were standardized.

The reuse, repair, and refurbishment sectors are all labor intensive. While automation is increasing to some extent, the session speakers explained that manual labor will likely always be required to disassemble, test, repair, and evaluate parts and products. This is a challenge for the sector as it requires training and experience and competition exists from other manufacturing industries.

The economics of reuse, repair, and refurbishment is another barrier. New products are becoming increasingly cheaper, and thus consumers are often swayed to buy new rather than pay for repair or buy a used device. Further, there is concern about additional costs associated with reuse or repair, such as potential future repair costs due to fears of decreased performance. In the case of EV LIB reuse for grid-scale energy applications, there is concern of increased insurance costs associated with the use of second-life batteries. Often, the most economical path for reuse is in other regions of the world (China, India, etc.) but this removes the materials from the U.S. supply chain.

Electronics Recycling Challenges

Barriers facing electronics recycling include product evolution, outdated infrastructure, hazardous materials (i.e., safety), and market (i.e., price drops). Thousands of new products enter the market annually, with diverse and changing compositions, materials and material grades, and form factors. While this presents a massive opportunity for electronics recyclers, it also poses an immense challenge as they need to determine the most effective and economical path for recovery.

In the U.S., electronics recycling typically involves bulk recovery through shredding. Therefore, while glass, plastics, steel, aluminum, and copper are readily recycled, existing infrastructure is limited in its ability to recover precious and critical metals such as gold, silver, palladium, lead, and REEs. Recovery of these elements requires a more focused extraction methodology.

Safety is another barrier to electronics recycling. Battery fires, explosion, accidents in the recycling facility, as well as exposure to hazardous materials (e.g., lead) are all safety concerns for recyclers.

Battery Recycling Challenges

Battery recycling is challenged by product evolution and lack of standardization, safety, transportation, and collection logistics, as well as lack of information to support EoL decision-making. The increased generation of mobile electronic devices as well as EVs relies on LIBs of various shapes, sizes, form factors, and chemistries. The lack of standardization of LIBs in various applications is a barrier to second-use applications as well as recycling operations. For example, LIBs no longer suitable for EVs could be used for grid-scale applications, however the lack of standardization means utilities must try to mix and match batteries, which is problematic. Similarly, recyclers who process batteries at EoL are challenged by the different chemistries and form factors.

Damaged LIBs are susceptible to ignition and as such, battery fires pose a significant challenge in the industry. Further, due to their ignitability, LIBs are listed as a Class 9 hazardous material and thus necessitate increased care and cost for transportation.

The current battery recycling infrastructure is largely designed around processing small-format batteries from e-waste. However, projections estimate EV batteries to dwarf batteries from e-waste within the next decade. This transition will necessitate a significant change in the collection, transportation, and processing logistics of battery recycling.

Another barrier to battery recycling is the lack of available data and information to support EoL decision-making. Practitioners must decide whether a battery can be reused (e.g., EV LIB used in an alternative application) or recycled. A key principle of the CE is to extend product and component life for as long as possible through reuse and repair. However, recyclers have little to no information about batteries entering their facility, specifically, cathode chemistry, form factor, history (e.g., use cycles), or remaining charge rate. This hinders recyclers' ability to choose the appropriate pathway for recovery. Additionally, the feasible reuse of batteries is impeded by a lack of performance metrics, best practice guides, or concrete financial data.

Finally, there is limited incentive or motivation for private investment in battery recovery and recycling. This is in part due to a lack of available information and data about the volume, timing, and condition of retired batteries, as well as the value of, and market for reused and recycled batteries. Such information is necessary to inform investment decisions. Moreover, there is limited publicly available information about the performance, quality, safety, and technical viability of reused batteries to support consumer trust and confidence and thus increase demand for reused batteries.

Solar Panel Recycling Challenges

The delay between now and when substantial amounts of modules will reach EoL is a challenge for solar recycling as it inhibits investment and development of collection and recovery infrastructure. PV generation and installation are still ramping up, and with panel lifetimes of ~30 years, EoL modules are not expected to reach a high enough volume to justify dedicated PV recycling facilities for many years. As a result, the U.S. does not currently have comprehensive solar panel collection or recycling infrastructure. Today, most panel recycling is carried out on existing glass recycling lines on a batch basis because of the low module volumes. Materials recovered typically include aluminum, cables, and glass, but recyclers fail to recover the semiconductor and other high-value materials.

High-value recycling processes are needed to recover valuable materials like silver, copper, and high-purity silicon. Current practices recover metallurgical-grade silicon, but improvement to solar grade would substantially increase the revenue potential of recycling and close the material loop within the solar supply chain. Similarly, PV glass is not currently recovered at a purity-level required to return to the solar supply chain.

The economics of solar panel recycling is also a major barrier. According session speakers, today in the U.S. it costs approximately $30 to process a single module, and revenue is roughly $3 per module. The cost to landfill a module is between $0.50-$1.80. Panel reuse could potentially generate $20 per module, but due to improved efficiency and reliability of new modules, consumers are reluctant to purchase second-use panels.

2.2 Needs to Address Challenges

Four key needs were brought to light through the workshop presentations, discussions, and Slido responses which are necessary to facilitate a transition to a CE for high-tech products. These included the need for accessible and findable data through publicly available repositories and registries, the development of standards and best practice guides, research and development, as well as education, outreach, and training programs.

Data and Information Sharing

Publicly available data and information exchange are necessary in the transition to a CE for high-tech products. Increasing the amount of information provided to – and shared among – CE stakeholders will enable and expand new and existing practices, programs, and markets. Table 2 provides examples of specific data needs identified in the workshop.

Table 2: Data Needs to Facilitate a CE for High-Tech Products

Material Level	- Material stocks and flows in the economy - Current and projected material demand/usage/ consumption - Hazardous material content and associated risk
Product Level	- Regionally distinct data on sales, collection, and disposition - Product sales projections - Product weights, material/chemical composition, and form factors - Product lifespans and performance specifications - Performance data for second-use applications - Product safety, risk, and mitigation (e.g., LIB ignition)
Market Level	- Reuse markets - Recycler market economies (e.g., commodity market price impact on recycling processes) - Materials marketplace or "clearing house" of quality-controlled materials or products
System Level	- Lifecycle inventory data (e.g., inputs of energy, water, and raw material, outputs to air, soil, water) - Geographic distribution of CE infrastructure including locations and processes associated with collection, reuse, repair, refurbishment, and recycling - Current and future technology options for product and material recovery

Major data gaps identified in the workshop include the flows of materials and product types through the U.S. economy. Material flow analyses and forecasts are hindered by the lack of information regarding the material content of products. Further, little information is publicly available about product sales, lifespans, or quantity reaching EoL, let alone EoL processing. Data about product composition, lifespan, and EoL processing is needed to develop CE systems and close material cycles. For example, in-use EV battery monitoring and degradation data could aid life expectancy projections, which could be used to inform supply forecasts and help identify viable second-use applications.

Information sharing must also be promoted to facilitate a CE and can take many forms. Publicly available databases, repositories, and registries can be managed by private and/or public institutions for use by CE stakeholders. Data publishers and stewards should follow the FAIR Data Principles of Findability, Accessibility, Interoperability, and Reusability to ensure effective data discovery and application [26].

Product labeling is another strategy, in which specific information such as material/chemical composition could be identified on a product or component (e.g., battery). This would enable information exchange between manufacturers and reuse or recycling stakeholders, providing the information necessary for safe handling, transport, storage, reuse, and recovery.

Information sharing requires transparency across product, market, and system levels. Transparent information exchange can enhance system performance, stimulate investment, and help strengthen relationships of stakeholders across the lifecycle of products and thereby promote circularity. Strategies are necessary to facilitate transparency while protecting proprietary information.

Information sharing also necessitates increased dialogue between stakeholders within and throughout the CE. This is necessary to understand different dimensions and recognize the diverse perspectives of various stakeholders. Communication channels must be enabled and supported which are participatory and inclusive.

Metrics, Frameworks, and Tools

Increased development, expansion, and coordination of metrics, frameworks, and system-level assessment tools are needed to better evaluate and facilitate a CE. Comprehensive assessment requires metrics pertaining to material usage and consumption, temporal attributes of materials and products, spatial and cross-sectoral distribution, as well as behavioral factors at the consumer and market levels. Framework development should then characterize the interconnected systems by expanding on the analysis of sustainability attributes across system levels (i.e., from product level to macro economy level). Further, transition indicators must be expanded and translated into financial metrics to support the development of new, circular business models. Finally, CE tools and frameworks must be incorporated in design processes to enable the inclusion of sustainability factors in conjunction with functionality and performance.

Standards and Specifications

Standardization of terminology, concepts, and principles is an important element in the transition to a CE. Consensus of terms across industries and agencies is needed to enable cross-sectoral data collection, management, and analysis, thereby promoting better communication and the effective exchange of information among market actors. This can best be achieved by convening public and private institutes, such NIST, the ISO, UNEP, the EU Commission, The REMADE Institute, as well as trade associations to get consensus on definitions ranging from high-level concepts to technical details and terminology.

Standardization of components, product lines, and across generations is also necessary to support consistency and reliability in the CE and help limit volatility in system. Standardization of components used in electronic products or PV systems (e.g., HDDs, batteries, junction boxes, inverters) allows for efficient repair and refurbishment, as well as simplified recycling processes. Standardization of batteries, particularly battery chemistry, module, and cell structure, is also needed to support reuse applications as well as improve battery recycling.

Process standardization is needed to standardize methods for reuse, repair, and recycling of high-tech products. Process standardization ensures environmentally and socially sound practices (e.g., worker safety), as well as promotes consistent material output. For example, reproducible standardized methods for battery discharge, safe handling, and transport, are necessary to ensure safe, effective, and consistent recovery of battery materials. Similarly, standardized high-value PV recycling processes can support the recovery of semiconductor and other high-value materials from solar modules.

Certification standards are also needed in the transition to a CE. In the reuse and refurbishment industries, standards need to be developed to verify an expected level of performance, quality, safety, and technical viability of reused or refurbished products. This requires benchmarking and verification measure development. Such standards will positively impact consumer trust and confidence in reuse and refurbished products. In the recycling industry, quality standards need to be developed that provide requirements, specifications, guidelines, or characteristics that can be used to ensure recycled materials are fit for re-entry into supply chains.

Research and Development

Workshop speakers and attendees identified many R&D needs to transition to a CE for high-tech products, ranging from high-level system analysis to scientific investigation and technology development. Specific R&D needs include the following:

- Materials science advancements in the reduction and/or replacement of critical materials
- Detection and separation mechanisms for the recovery of high-value material constituents (e.g., critical metals, solar grade silicon)
- Advancement of AI and robotics to identify, assess, and/or disassemble devices
- Rapid material composition identification
- Development of product and/or material traceability system (e.g., blockchain as distributed ledger for tracing material content and product life)
- Analysis of purity tolerances for recycled feedstocks
- Protocol development for assessing the state of spent batteries

In many cases, the transition from laboratory and bench-scale research to pilot projects and eventually commercialization is hindered by lack of investment. This is particularly the case for solar modules and large-format batteries (e.g., EV LIBs) due to the low quantity of products currently reaching EoL. This situation is not justification for delayed research on recovery methods, but rather supports the need for government-funded R&D in the field. Government-funded R&D could enable private investment in sectors of the CE by providing the data and information necessary to alleviate market uncertainties and thus prompting the development and deployment of cost-efficient reuse, refurbishment, and recycling processes.

Education and Outreach

Awareness regarding proper EoL management of electronic products, batteries, and solar PV modules arose as a key need to facilitate a CE for these products. Education needs span the stakeholders involved throughout the lifespan of products. Targeted information campaigns should focus on the following:

- Product designers and manufacturers: design guidelines that incorporate DfR with functionality, performance, and cost
- Automotive recyclers and scrapyards: how to decommission EV LIBs and where to send for reuse or recycling
- Utility scale developers and operators: how to decommission large-format battery assemblies and solar PV systems and where to send for recycling
- Government agencies and public institutions: sustainable procurement guidelines and how to manage electronic equipment at EoL
- General consumers: guidelines on sustainable procurement, proper data management and destruction, and where to take unwanted or EoL equipment
- Battery-containing equipment handlers and transporters: how to safely handle and transport LIBs and LIB-containing equipment to reduce ignition risk
- General public: disassembly, repair, and refurbishment guidelines and training opportunities

3 Proposed NIST Action Items

NIST can play an essential role in facilitating the transformation to a CE for high-tech products. Based on the outcomes of the workshop, four key areas of NIST action items were identified: Data and databases, standards development, R&D, and education/outreach and training.

Data and Databases

NIST can provide data repositories and registries following the FAIR data principles (Findability, Accessibility, Interoperability, and Reusability). All data infrastructure should be publicly accessible and interpretable by all stakeholders involved in the CE. Where data exists, NIST can aggregate or make it accessible through comprehensive data registries and repositories. NIST can also fill many of the data gaps identified in this workshop, specifically:

- Identification of material compositions and forms of new products
- Geographic distribution of CE infrastructure including locations and processes associated with collection, reuse, repair, refurbishment, and recycling
- Material and product stocks and flows in the U.S. economy
- Performance statistics and financial data to support reuse and repair (particularly for batteries)
- A materials marketplace or "clearing house" of quality controlled (QC'd) materials or products

Standards

NIST can develop the standardization protocols and standards necessary to support consistency and reliability in the CE. Standards development requires verification methods which rely on extensive metrology and benchmarking, tasks NIST has vast experience performing. Examples of standards NIST could develop include the following:

- Product design
- Performance metrics for reuse/repaired products
- Information standards for supply chains, recycled materials quality control, best practice guides (e.g., data wiping/erasure, assembly/disassembly, battery handling and decommissioning), expected lifetime certification, battery transport, discharge, and safety
- Standard reference materials (SRMs) for the composition of recycled materials

R&D

NIST can support basic and applied research necessary to facilitate a CE. In particular, NIST can perform pre-competitive research that is too expensive or specialized for any one company to undertake, and, as such, can move the whole industry forward. Examples of R&D that NIST can perform or support include:

- Purity tolerances for post-consumer feedstocks
- Rapid material composition fingerprinting
- Publicity of product materials/composition, while protecting IP
- Materials science for the reduction/replacement of rare materials
- Analytical methodologies for the assessment of recycled material composition
- Protocol development for assessing the state of spent batteries
- Blockchain as distributed ledger for tracing material content
- Application of AI and robotics to identify, assess, and/or disassemble devices
- Neutron activation analysis for detection of rare earth elements
- High-value materials recovery technologies and processes (e.g., critical metals, solar grade silicon)

Education, Training, and Consortia Development

NIST can support the CE by providing education and guidelines to CE stakeholders on the following topics:

- Design for repair and recycling
- Data wiping/erasure
- Best practice guidelines for reuse, refurbishment, and recycling
- Publicizing a repairability index to rate new products on their ability to be repaired.

NIST can also support the CE through workforce development and outreach programs. Such efforts could include K-12 education activities, collegiate research and academic programs, as well as applied reuse, refurbishing, and recycling apprenticeships and training programs.

Additionally, NIST can convene stakeholders from throughout the high-tech CE industries to identify and prioritize long-term, pre-competitive industrial and technical challenges. A CE consortium can involve research and testing, technology and process development, and development of technical roadmaps. A NIST-supported consortium will create the infrastructure necessary for more efficient transfer of data, information, and technology and thereby strengthen the CE in the U.S.

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Appendix A: Agenda

Time (ET)	Wednesday; Jan 27, 2021			Thursday; Jan 28, 2021
10:00	Intro to NIST and this workshop			Discussion of day 1 outcomes and agenda for day 2
10:15	Keynote 1 - William McDonough			Keynote 2 - Thomas Graedel
10:30				
10:45				
11:00				
11:15	Break			Break
11:30	Session 1: How do we Create a Circular Economy?			Session 4: Reuse, Repair, and Refurbishment in a Circular Economy
11:45				
12:00				
12:15				
12:30				
12:45				
1:00	Lunch Break + Networking			Lunch Break + Networking
1:15				
1:30				
1:45	Session 2a: Electronics Recycling Challenges	Session 2b: Battery Recycling Challenges	Session 2c: Solar Panel Recycling Challenges	Session 5: Best Practices for a Circular Economy
2:00				
2:15				
2:30				
2:45	Session 2a Breakout	Session 2b Breakout	Session 2c Breakout	
3:00				
3:15	Break			Break
3:30	Session 3: Boundary-spanning tools to support a circular economy			Breakout Session
3:45				
4:00				
4:15				
4:30				
4:45				Closing remarks

Appendix B. Workshop Participants

Name	Organization
Adina Renee Adler	ISRI
Adam Shine	Sunnking
Adrian Grace	ERI Direct
Agustin Correa	Triciclos
Ahmad Al Khowaiter	ARAMCO
Alberta Carpenter	NREL
Alessandra Hool	ESM Foundation
Aleta Daniels	KPWB
Alison Taylor	Indiana Department of Environmental Management
Alison Kinn Bennett	US EPA
Amanda Forster	NIST
Andi Parins	Dynamic Lifecycle Innovations
Andre Mitchell	Cummins
Andrew C McManus	Gannon-Scott
Andrew Loebl	Albemarle Corporation
Anna Kavalieris	US DOC
Anne Marie Green	PIRG
Anya Bouarab	Geomega
Ashley Gaulding	NREL
August Martin	ERM
Becky Campbell	First Solar
Belal Aldokhayel	n/a
Benjamin Gallagher	EPRI
Bill Fisher	n/a
Bill Healy	n/a
Billy Johnson	ISRI
Bob Allen	NREL
Bob Maughon	SABIC
Bob Newman	DHS
Brad Powell	Emerson Collective
Branden Schwaebe	University of California, Irvine
Brian Freiburger	DHS
Brian Yates	Dell
Brijesh Krishnan	Cummins
Evelyn Butler	Solar Energy Industries Association
Callie Babbitt	RIT
Cara Libby	EPRI
Carol Handwerker	Purdue
Casey Westhoff	Umicore
Cassie Gruber	Jabil
Cate Berard	US DOE
Celeste Weaver	William McDonough + Partners
Cheryl Coleman	ISRI
Chris Newman	US EPA
Christopher Glaubensklee	University of California, Irvine

Christopher Rooney	Empire State Development's Division of Science, Technology and Innovation (ESD/NYSTAR)
Christopher Szakal	NIST
Christy Bujnovszky	Maryland Department of the Environment
Clifford Lundgren	n/a
Corey Dehmey	SERI
Craig Boswell	Hobi
Craig McOmie	Wyoming Department of Environmental Quality
Cram Matthew	n/a
Cynthia Jenks	Argonne National Laboratory
Dan Hebert	Aces Group
Danielle Azoulay	Loreal
Darien Sturges	n/a
Darlene Steward	NREL
Dave Butry	NIST
Dave Holbrook	NIST
David Mrgich	Maryland Department of the Environment
David Wagger	ISRI
Deanna Garner	Indiana Department of Environmental Management
Dee Durham	Plastic Free Delaware
Dennis Coen	Personal
Don Lipkin	GE
Donald Karner	Electric-Applications
Douglas Smith	Sony
Dwarak Ravikumar	NREL
Edwin Mopas	SunPower Corporation
n/a	Electric Power
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Elena Vidanoska	ERI Direct
Elina Kasman	Argonne National Laboratory
Elise Owen	US EPA
Engelbrecht Wig	n/a
Eric Lin	NIST
Eric Lundgren	Big Battery
Evan Thomas	Argonne National Laboratory
Evan Wallace	NIST
Evelyn Butler	n/a
Flavia Calvar	Titan Advanced Energy Solutions
Aaron Forster	n/a
Frank Gayle	NIST
Frank Kuijpers	SABIC
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Gordon Gillerman	NIST
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Heather Buchanan	NREL
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Helen Mearns	Department of Homeland Security S&T CSAC
Henry	n/a
Holly Elwood	US EPA
Hongyue Jin	University of Arizona
Indu Kheterpal	Albemarle Corporation
Janice Johnson	US EPA
Jason Marshall	ACES Group
Jason Linnell	National Center for Electronics Recycling (NCER)
Jeff Fagan	NIST
Jeff Spangenberger	Argonne National Laboratory
Jenn Lynch	NIST
Jenna Larkin	US EPA
Jennifer Wang	Albemarle Corporation
Jessica Durham	Argonne National Laboratory
Jessica Young	US EPA
Jim Guerra	Maine Department of Environmental Protection
Jim Warren	NIST
Jiri Horalek	RBC Group
Joanne Larson	Seagate
Joannie Chin	NIST
Joe Bush	Battery Resourcers
Joel Kern	Veterans Alliance Resourcing, Inc.
John Bahouth	Apex Clean Energy
John Bonevich	NIST
JOHN Glaser	US EPA
John Katz	US EPA
John Kucklick	NIST
John Perkins	NIST
John Rosso	SGS North America Minerals
Joseph Capuano	US GAO
Josh Lepawsky	Memorial University of Newfoundland
Joshua Kneifel	NIST
Joyce Mount	ERI Direct
Judy Guzzo	GE Company
Julie Schoenung	University of California, Irvine
Julien Walzberg	NREL
Kali Frost	Purdue University
Kalman Migler	NIST
Karen Orvos-Toth	Halliburton
Kate Rimmer	NIST
Kate Beers	NITS
kathleen fiehrer	Intel
Kathleen Maleski	GE Company
Kathy Lett	US EPA
Katja Iversen	n/a
Kavita Thakkar	ERM

KC Morris	NIST
Kelsea Schumacher	NIST
Kevin Leary	US DOT
Kimberly Richardson	Q-Cells
Komal Kooduvalli	RIT
Kristin Fitzgerald	US EPA
Kulwinder Dhindsa	Nissan-USA
Kyle Wiens	iFixit
Laid Sahraoui	R3-Tech
LaKesha P.	NIST
Lana Lief	CalRecycle
Laura Espinal	NIST
Lawrence M Novicky	n/a
Leah Kauffman	NIST
Zheng Li	Virginia Tech University
Ligia Smith	n/a
Linda Gaines	Argonne National Laboratory
Lipiin Sung	NIST
Lynn Rubinstein	NERC
Maan	n/a
Magdalena Bobadilla	TriCiclos
Majid Alipanah	University of Arizona
Maria Curry-Nkansah	NREL
Marian Adusei	RIT
Marine Nortier	CEA Tech
Marivel Simmons	Department of Homeland Security
Mark Buckley	One Boat Collaborative
Mark Caffarey	Umicore
Mark Quiroz	n/a
Mark Scott	Tech Reset
Martha Somerman	NIH
Martin Green	NIST
Mary Ann Schelde	NYS Department of Environmental Conservation
Mary Beth Sheridan	US EPA
Matt Cram	Aerion Corp
Matt Sheehan	CalRecycle
Megan Pryor	Maine Department of Environmental Protection
Megan Quinn	Industry Dive
Meghan Stenslien	Think Dynamic
Mel Gregg	Intel
Melissa Bilec	Uniersity of Pittsburg
Michael Bax	Call2Recycle
Michael Morimoto	General Services Administration
Michelle Chuaprasert	Intel
Mike McGarragan	SGS North America Minerals
Mike Winchester	NIST
Nabil Nasr	Remade Institute
Nakia Simon	Stellatis
Nancy Gillis	Green Electronics Council

Nehika Mathur	Purdue University
Nick Abbatiello	Dell
Nick Barbosa	NIST
Patty McKenzie	SERI
Pauline Truong	NIST
Peter Afiuny	Urban Mining Company
Peter H van Erp	NYS Department of Environmental Conservation
Peter Templeton	Cradle to Cradle Products Innovation Institute
Phoebe O'Connor	US EPA
Pierre Huyn	Hitachi
Priscilla Halloran	US EPA
Priya Govindarajan	Intel
Maheswar Satpathy	Utkal University
Jim Purekal	n/a
Rachel Trello	NIST
Ramesh Bhave	Oak Ridge National Laboratory
Rebecca Ranich	Exenico
Rick Thompson	Dell
Rob Carvalho	QML, Inc.
Rod Eggert	Colorado School of Mines
Roland Kaeppner	NEOM
Ron Lembke	University of Nevada, Reno
Ronald Jones	NIST
Ruby	Beauty Kitchen
Ryan Richards	Colorado School of Mines
Sandra Cannon	Eco Purchasing
Santanu Chaudhuri	Argonne National Laboratory
Sara Orski	NIST
Sean DeVries	SERI
Shab Fardanesh	US DOE
Shahana Althaf	Yale University
Sharada	SERI
Shubhankar Upasani	NREL
Shy Sayadi	n/a
Sravan Chalasani	Lawrence Berkeley National Laboratory (LBNL)
Stephanie Hooker	NIST
Stephanie Shaw	EPRI
Steve Tolen	Indie Power Systems
Suhail Khan	ACES Group
Susan Gilbert-Miller	Green Electronics Council
SWR	NIST
Tamae Maeda Wong	NIST
Taylor L Curtis	NREL
n/a	TeraSci Industries, Inc.
Teresa Barnes	NREL
Terry Goolsby	University of Maryland
Thomas Maani	Purdue University
Thomas Graedel	Yale University
Thomas Novak	Schnitzer Steel

Tim McIntyre	Oak Ridge National Laboratory
TJ	n/a
Todd Coy	Kinsbursky
Tom Theis	University of Illinois at Chicago
Toshi Fukui	Honda
Venus Welch-White	US EPA
Vishal S Shirwadkar	Cummins
Vivek Prabhu	NIST
William McDonough	William McDonough + Partners
xiaohong	NIST
Y. Zhou	GE Company
Zachary Trautt	NIST

Appendix C. Detailed Session Content

Following introductory remarks, the workshop began both days with a plenary talk from invited experts from industry and academia who set the context for the more focused topical sessions that followed. This appendix summarizes the perspectives offered by the plenary speakers, session speakers, as well as discussion sessions.

Plenary 1: William McDonough

William McDonough is a globally recognized leader in sustainable design and development. He has written and lectured extensively on design as the first signal of human intention highlighted in his 2002 book “Cradle to Cradle: Remaking the Way We Make Things.” He advises global leaders through McDonough Innovation and is an architect with William McDonough Partners. He also created the Cradle to Cradle Certified™ Products Program, through his other firm, MBDC, and co-founded the Cradle to Cradle Products Innovation Institute, which administers the program. Cradle to Cradle Certified™ is an independent, science-based, third-party, multi-attribute product standard recognized by the world’s leading retailers, including Amazon, Home Depot, Walgreens, and Walmart. Time magazine recognized him as a “Hero for the Planet,” noting: “His utopianism is grounded in a unified philosophy that—in demonstrable and practical ways—is changing the design of the world," and in 2019 Fortune magazine named him #24 of the World's 50 Greatest Leaders.

In his plenary address, *“*Cradle to Cradle: Circular Economy in the High-Tech World,” Mr. McDonough began by explaining how he came to understand what “high-tech” means. After growing up in Japan and learning of Hiroshima, Mr. McDonough was curious how things could be created that were so destructive in so little time. A professor at Dartmouth presented him with the theory of relativity equation ($E=mc^2$) and told him if he could solve it, he’d have the answer. Although Mr. McDonough couldn’t solve the equation, he realized that you must start with a number (c) and when squared it became immense if m is positive, thus E is almost always infinite. He related this to energy from the sun (physics) and materials from the earth (chemistry), which come together to make life (biology).

Mr. McDonough expanded that idea into his architecture, striving to make a building like a tree: emitting oxygen, sequestering carbon, etc. This transformed over time to not just include building design, but also building components, products, and materials. He spearheaded cradle to cradle design, incorporating many biological principles including waste as food, and the need to respect diversity. Mr. McDonough further explained cradle to cradle design as including the following:

- Design for use and next use without EoL
- Products as service
- Combining natural intelligence with artificial intelligence
- Designing for the biosphere and the atmosphere
- Safe products first – make good products and then recirculate them

Cradle to cradle is therefore about quality while the circular economy is about quantity: we must make quality products with safe materials and circulate them in the economy. With each design Mr. McDonough follows the same value statement: how do we love all the children of all species for all time? He argues that design must be guided by values, and follow the below path, demonstrating the value in the final product:

Values – Principles – Visions – Goals – Strategies – Tactics – Metrics – Value

Mr. McDonough discussed that we are in the Anthropocene epoch, as global human-made mass now exceeds all living mass, and humans manage the earth. As a result, we need new design. He argued that regulation can be a signal of a design failure, and that climate change is also the result of a design problem. Future design, he argued, can't focus on being "less bad", because that insinuates a less monotonous, unsafe, unhealthy, and unjust world – with less polluted air, soil, water, and power – which is economically driven. Instead, we must "be good" to support a "delightfully diverse, safe, healthy, and just world – with clean air, soil, water, and power – [which can be] economically, equitably, ecologically, and elegantly enjoyed".

Plenary 2: Thomas Graedel

Thomas Graedel is the Clifton R. Musser Professor Emeritus of Industrial Ecology and Professor Emeritus of Chemical Engineering at Yale University. Professor Graedel joined Yale University in 1997 after 27 years at AT&T Bell Laboratories. One of the founders of the field of industrial ecology, he co-authored the first textbook in that specialty and has published extensively and lectured widely on industrial ecology's implementation and implications. He was the inaugural President of the International Society for Industrial Ecology (ISIE) from 2002-2004 and winner of the 2007 ISIE Society Prize for excellence in industrial ecology research. He has served three terms on the United Nations International Resource Panel and he was elected to the U.S. National Academy of Engineering in 2002.

In his plenary address, "Are There Limits to Circularity?" Professor Graedel spoke to the major constraints facing the CE, specifically outlining five intrinsic limits:

1. Products designed to be dissipative (lost by design)

   Some products, such as fireworks, galvanized steel infrastructure, and brake pads, are designed with the intent that some fraction of materials or components are dissipated into the environment, never to be recovered. Professor Graedel discussed recent research on dissipative uses and recovery of materials, specifying minerals lost by design, those currently unrecyclable (i.e., no recovery technology exists or cannot recover into usable form), those that are potentially recyclable (i.e., recycling technologies exist), and unspecified (elements with minor uses). He presented the periodic table displayed in Figure A1, explaining that the center of the table is largely blue, signifying that the major metals – which are major constituents of many products – are recoverable/recyclable. But many elements have large yellow wedges (currently unrecyclable), and a few with significant red wedges (e.g., roughly 20-25 % of zinc is dissipated by design). The dissipative and currently unrecyclable elements are now a major constraint to a CE.

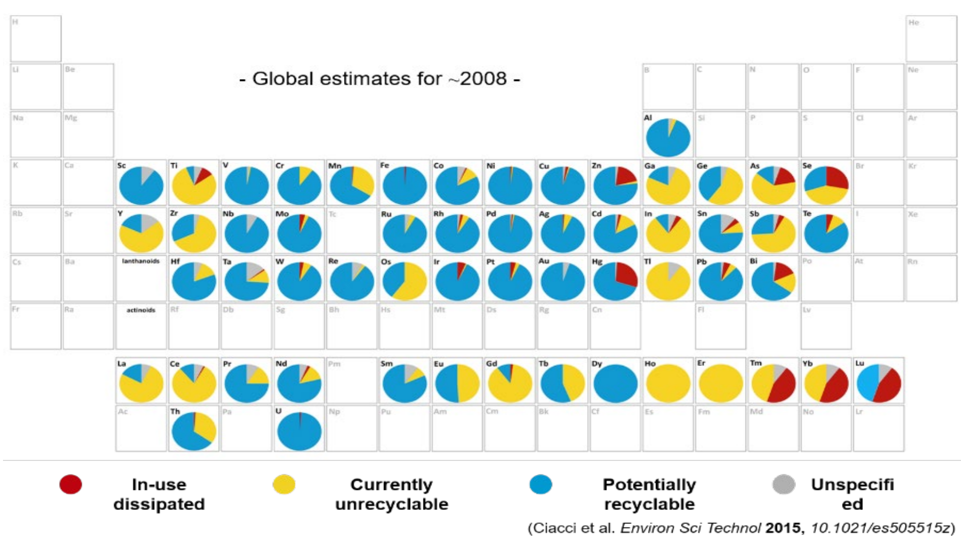


Figure A1: Periodic table displaying dissipative uses and recycling potential of elements

2. Final sinks challenge

   Some materials we no longer want in the economy but are unsure of how to process or store them. Professor Graedel identified radioactive waste and cadmium coatings of airplane landing gear as examples of problematic materials in which a final sink (end-of-life resting place) has yet to be determined. A CE should rely on clean materials cycles such that hazardous or toxic materials are kept out of the economy. However, problematic materials, especially those coming out of a long service life, will persist, and Professor Graedel calls for the need for final sinks to keep those materials from reentering the materials flow cycle.

3. Lack of commitment to reuse

   Professor Graedel identified three examples of a lack of commitment to reuse. First, he spoke of "comatose stock" – material that in principle could be recovered for reuse but would be too expensive to do so, such as an abandoned steel bridge. Second, and more commonly, he explained "hibernating stock" as materials which will likely be reused or recycled but are stored in a drawer or closet for the time being. Last, he spoke of materials thoughtlessly discarded in the trash, never to be recovered or recycled. The lack of commitment to reuse highlights the human element as a key part of the CE challenge.

4. Failures in design

   A major constraint to a CE is that products were never designed with the idea of making them easy to repair or recycle. Professor Graedel emphasized that if you are unable to take something apart (e.g., a complex engine), then you are unlikely to be able to reuse the constituents. Refurbishment requires that you retrieve, replace, and perhaps remanufacture parts. But if the product is not designed to enable that, it makes remanufacturing difficult, if not impossible. Professor Graedel spoke to the increased complexity of smaller devices and commented on the number of elements from the periodic table (~65) in a typical cell phone. He argued that it is almost a guarantee that we will never be able to recover perhaps a third to a half of those materials.

5. The spatial challenge

   Global flows of materials have increased greatly over recent decades. Professor Graedel discussed material flow rates between 2002 and 2015, pointing out that in those 13 years, humanity around the planet increased material use by 53 %. Materials are distributed in products around the world, and in the past decade or two have especially been distributed in parts of the world whose nascent economies are in the process of growing. He spoke of nickel imports and exports in Australia, a highly developed country that mines nickel ores, but exports it for processing, then imports nickel-containing products, only to discard them at EoL due to lack of recovery infrastructure. The situation becomes more challenging as modern electronics decrease in size (smaller amounts of materials) yet rely on 50-60 different elements which all come from different material deposits. Recovery of those materials necessitates mimicking much of the technology that was used in ore extraction. Professor Graedel pointed out that three facilities exist which can recover materials from electronics (e.g., Umicore in Belgium has the highest current recovery, at 17 elements) but these facilities are expensive and dispersed globally. Professor Graedel argues that if we are serious about a CE, then we need to either build Umicore-style reprocessing facilities all over the world (at a very high cost), or we need to have an economical ocean shipping system, which comes with its own environmental costs.

Professor Graedel closed his plenary with two final thoughts: 1) none of his discussion should be interpreted to mean that moving toward a more CE is a bad idea, only that the concept has inherent limits, some immutable, some not, and 2) we will make more rapid progress toward a *more circular* economy if we realize the systemic limits to our ambitions and make those limits the targets of our efforts.

Session 1: How do we Create a Circular Economy?

Nik Engineer, Executive Lead – North America, Ellen MacArthur Foundation

Mr. Engineer introduced the EMF and the organization's mission to accelerate the transition to a circular economy. They work to achieve this mission by:

1. promoting and developing the idea of a CE
2. engaging and inspiring key actors in the system
3. mobilizing systems solutions at scale, globally

Mr. Engineer explained that while they began in secondary education, they have expanded to five areas including: business, learning (including design), systemic initiatives, institutions, governments and cities, and insight and analysis. In all their work, the EMF promotes three principles of a CE, all performed by design: eliminate waste and pollution, keep products and materials in use, and regenerate natural systems. Mr. Engineer presented the EMF's 2021 agenda which includes efforts specifically focused on biodiversity, climate change, policy to enable scale, design, measurement, and plastics.

Gregory Keoleian, Professor of Sustainable Systems, University of Michigan

Professor Keoleian discussed his research developing a CE framework for automobiles, including metrics, strategies, and insights. Regarding metrics, Professor Keoleian stated that characterization of CE and life cycle design strategies typically rely on recycled content (%), recyclability (% recycled), renewable energy (%, generally not total fuel cycle based), biobased materials (%), and service life (vehicle miles traveled (VMT) or age). Examples of life cycle analysis (LCA) metrics include life cycle greenhouse gas (GHG) emissions, life cycle primary energy (renewable, non-renewable), and resource depletion. Sustainability performance is generally evaluated based on LCA metrics applied at the economy wide scale.

Professor Keoleian discussed recent research on a CE framework for automobiles, in which his team has modeled material and energy flows for the industry and specific engine types. Their framework enabled them to compare internal combustion engine vehicles (ICEV) and battery electric vehicles (BEV) based on metrics such as recycled material inputs, recyclability, as well as life cycle renewable energy. Their findings indicate that the energy and carbon intensity of secondary material is significantly lower than that of virgin materials. Further, ICEV future market will be limited by the carbon intensity of its fuel source, and vehicle electrification and grid decarbonization are key strategies for accelerating sustainability.

Professor Keoleian provided several CE insights based on his research in the automotive industry. On the topic of frameworks and tools, he explained that the foundations for CE are rooted in industrial ecology, life cycle design, LCA, and green engineering. He argues that renewable energy tracking should be included, as many current constructs focus only on materials. Regarding metrics, he stated that there is a diverse range of CE metrics/indicators being proposed which focus on closed loops and characterizing interconnected product systems. However, they do not necessarily ensure enhanced sustainability performance. Current CE strategies are not inherently sustainable, and he argues that strategies may conflict. System level assessment tools such as LCA are required to evaluate sustainability performance. He provides areas for future research including standards for functional unit definition of interconnected product systems, analyzing sustainability across system levels (product level to macro economy levels), and accounting for material primary production displacement rates and CE rebound effects.

Alessandra Hool, CEO, ESM Foundation - Foundation for Rare Metals

Ms. Hool resides in Switzerland and thus much of her presentation provided a European context of the CE. She discussed materials from the periodic table, presenting the same image as Professor Graedel (Figure A1) and explained that actual recycling rates of critical metals are not even close to their potential. She spoke to the reality of unavailable data, stating that it is not even possible to document the flow of materials entering the system because material stocks and flows are largely unknown. She provided cobalt flows in the EU as an example used Figure A2 to demonstrate where available data exists (green), where little information is available (orange pattern), and where no information has been found (red boxes).

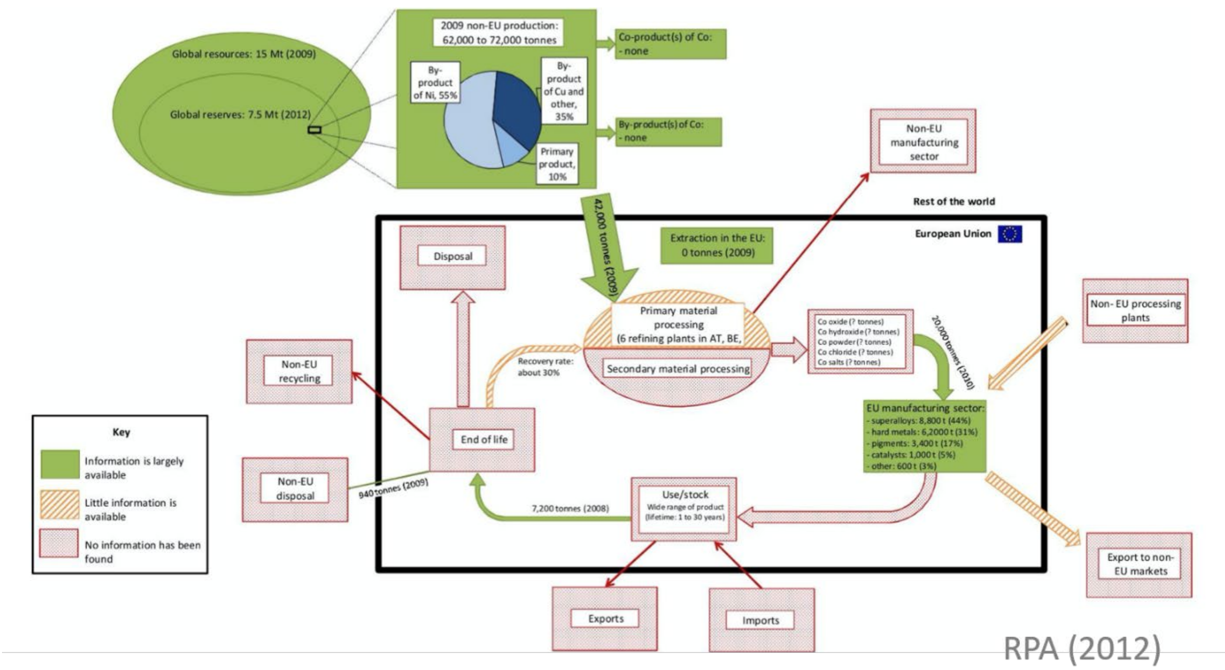


Figure A2: Cobalt flows in the EU: available data

Ms. Hool presented specific challenges facing the circularity of minor metals. These included the following:

- Lack of data
- Small amounts of CRM per product
- Mass-based recovery targets
- Complex material compositions
- Logistic challenges
- Highly price dependent

She further explained three strategies to incentivize CRM circularity. First, increase the price of primary raw materials to make them relatively more expensive. This includes integrating external costs such that real costs of material consumption are reflected, including environmental and social costs of the value chain. By monetizing these costs losses can be compensated for and less harmful materials (such as secondary raw materials) become competitive. But there is a long way to go as integrating external costs requires transparency and international collaboration. The second incentive is to increase CRM circularity is through regulation. Regulation could set mandatory raw material-based recovery targets, prescribe information flows while simultaneously protecting company confidentiality, provide funding for innovations between basic R&D and commercial success, incentivize standardization, and support labeling of best-practice companies and/or products. Last, incentivize CRM circularity by creating business advantages. Miss Hool discussed two examples, recovery of neodymium and dysprosium from NdFeB magnets in Hitachi Group hard disk drives (HDDs), and rhenium from jet engine turbine blades. Using the examples, she explained how business-to-business arrangements can be organized to optimize the value chain and support material circularity.

Maria Curry-Nkansah, Senior Research Advisor, NREL

Dr. Curry-Nkansah provided an overview of NREL and the agency's three-tiered focus: (1) Integrated Energy Pathways, (2) Electrons to Molecules, and (3) Circular Economy for Energy Materials, the latter being the focus of the remainder of her talk. She provided CE projections for renewable energy technologies, specifically lithium-ion car batteries, photovoltaics, and wind turbines. The projections included waste volumes, material value, material content, challenges, current recycling processes and reuse alternatives. Figure A3 displays the projections for car LIBs and photovoltaics.

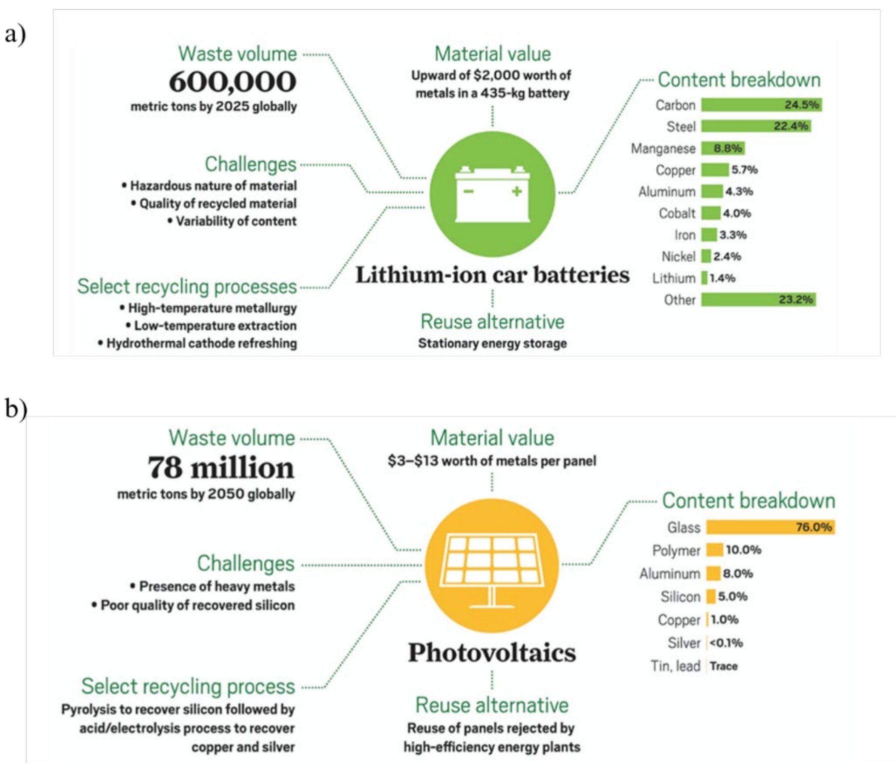


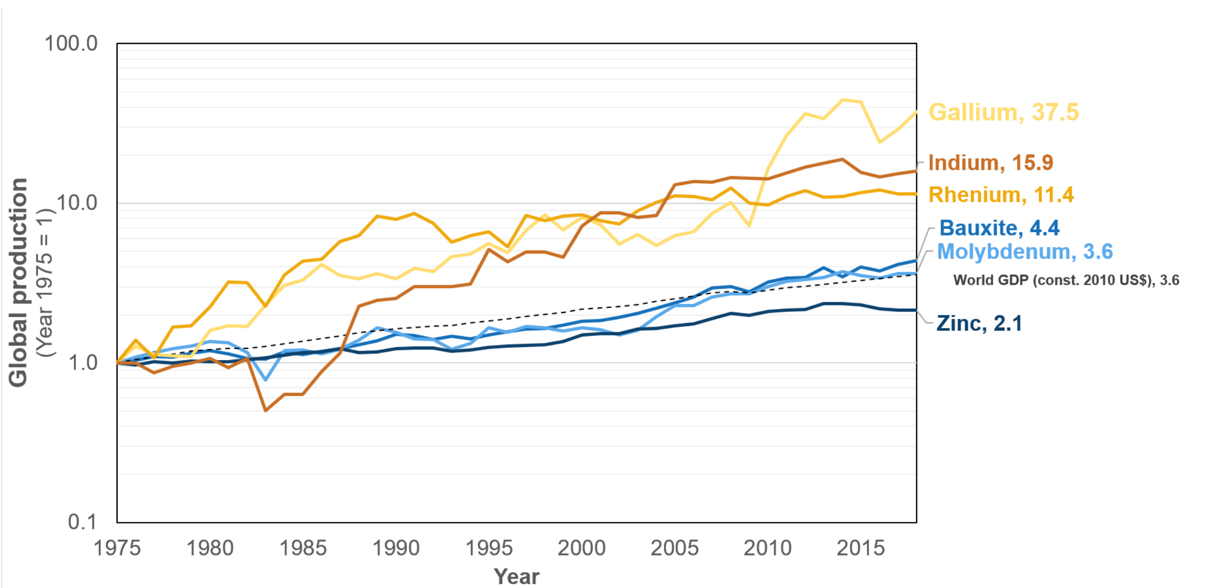
Figure A3: Renewable Energy Circular Economy Projections: a) lithium-ion car batteries, b) Photovoltaics

Dr. Curry-Nkansah stated the goal of NREL's CE for Energy Materials program is to focus on research that establishes knowledge and technology for design, reduce, reuse, or recycle to create a CE for energy-relevant and energy-intensive materials, processes, and technologies. The program has three initiatives focused on 1) polymer and composites, 2) advanced energy materials and technologies, and 3) future adaptive materials for energy systems (this initiative is still in the planning stages). She explained that to accomplish their goal, they work cross-functionally with subject-matter experts in analysis modeling, materials processing, reliability lifetime testing, and device systems fabrication. Dr. Curry-Nkansah provided several examples of ongoing research and consortiums at NREL. She also provided some areas for possible collaboration with NIST which included:

- Quantitative and qualitative research and analysis, and industry stakeholder engagement
- Reliability and safety metrics for reuse/repair for reuse applications
- Industry standards to include circular and ethical reuse/repair for reuse principles
- Codes, standards, and regulatory requirements applicable to reuse/repair for reuse applications
- Future design needs for secondary use applications and in-field repair

Nedal Nassar, Chief, Materials Flow Analysis Section, USGS

Dr. Nassar explained that the drive towards faster, smaller, and smarter technology has accelerated the use of mineral commodities, especially minor metals. He provided a graph (Figure A4) demonstrating the increased production since 1975 of major commodities (bauxite, molybdenum, zinc) and minor metals (gallium, indium, rhenium). Projection of major metals has largely increased along with GDP, adjusted for inflation, while minor metals have increased substantially faster. However, minor metals are generally by-products of the major commodities and thus supply of these materials is inelastic, i.e., not necessarily responsive to demand signals. In fact, based on information Dr. Nassar presented, 31 of the elements used in electronics (Figure 1), are almost entirely (>70 %) produced as a byproduct of major metals. This could be problematic if the demand for these byproduct commodities continues to increase compared to their host metals.



Data source: Kelly, T.D., and Matos, G.R., comps., 2017, Historical statistics for mineral and material commodities in the United States (2016 version): U.S. Geological Survey Data Series 140, available at https://minerals.usgs.gov/minerals/pubs/historical-statistics/; USGS Minerals Yearbooks and Mineral Commodity Summaries; GDP data from World Bank.

Figure A4: Global production of major and minor metals since 1975

Dr. Nassar explained another concern regarding the production of minor metals, that production of these commodities is highly concentrated. China, Australia, Brazil, the Democratic Republic of Congo, and South Africa all have large concentrations of specific mineral commodities. Dr. Nassar discussed the development of a risk modeling framework to identify and assess commodities most critical to the U.S. manufacturing sector and whose supply chains pose the greatest risk. He argues that the CE strategies of reducing losses and increasing recycling are key to reducing the overall supply risk. He discussed the development of scenarios to determine which strategies are most effective for achieving a specific goal for each mineral commodity and explained that tracking minerals throughout their lifecycle helps to quantify losses and identify opportunities at different stages of the supply chain. Examining how flows evolve over time helps to detect trends and highlight their impacts while assessing stocks of mineral commodities in-use informs "above-ground" resource endowments, economic development, and recycling potential. For example, forecasts project solar to comprise the largest share of globally installed electricity generation by 2041, but solar PV technologies require many minor metals (e.g., silver, cadmium, tellurium, indium, gallium, selenium, and germanium), all of which are produced as byproducts to host metals.

Speaker Q&A

Questions for the speakers included the following:

- How do we address the paradox that improvements in material use efficiency (e.g., tantalum in electronics) contributes to lower recycling rates since it becomes uneconomical to recover the tiny amounts of tantalum in the device for example. Do the benefits outweigh the dynamic?

  Response (paraphrased): Dr. Nassar responded that this is an issue. It becomes even more of an issue when we try to miniaturize as well also substitute, and results in decreased economic opportunity for recovery at EoL. Whether there is a net benefit is dependent on a case-by-case basis. That's why we need these kinds of analyses to figure out what makes sense and is it helpful or harmful at the end of the day. Mr. Engineer provided an analogy of small format plastic packaging. It will never be economical to recycle small plastic packaging. We simply must design away from those products. Professor Keoleian added that when markets aren't working, one needs to look at policies and regulation. When there are regulations requiring takeback of products that will clearly incentivize requirements for designers to come up with systems that are better for materials management. In this conversation we must consider alignment of the technology, markets, and the policy. All are critical levers. The other is the consumer and their understanding of these factors in terms of sustainability. Hool stated that this is a field where regulation has its place if it's not possible to solve it technologically.

- What certified reference materials should be produced to help with the CE?

  Response (paraphrased): Hool stated that a problem with reference materials is that the technologies are evolving so fast, it's hard to stay up with that. Dr. Curry-Nkansah added that NREL is researching the recycling of wind turbine blades into cement, and specification would be useful to ensure mixtures do not impact the curing process or structural integrity of concrete. Dr. Keoleian stated that separation of materials and being able to identify materials well is very important. Still facing economics. Virgin resources are relatively inexpensive.

- To what extend can landfills be viewed as a source of hibernating stock as demand pressures and technology allow?

  Response (paraphrased): Dr. Nassar responded with the question what is the quality of that resource? It's not just about quantity, it's about quality. In general, there may be steps in the supply chain where it may not have to go to the landfill. Beckons the question: what is worth going after? Dr. Keoleian further stated that it really will come down to the concentration of those materials in the landfill. What does it take in terms of resource to separate and recover the material? What is the quality of the ores, minerals? Takes better technology and more energy to extract and refine the materials. Can it be separated out economically? Dr. Curry-Nkansah responded that it is worth doing a study, Europe is studying their landfills and finding they can acquire more minerals from their landfills than is possible from iron/ore deposits. They think it's going to be economical. It would be good to at least study the opportunity. Hool supported that, saying that this is happening, and it is funded by EU commission.

- With Biden now electrifying the entire US fleet, can you comment on the best circular solutions for repurposing underutilized EV battery packs in the US?

  Response (paraphrased): Dr. Keoleian responded that we could dramatically reduce our impacts in terms of climate change by electrifying our vehicles, and OEMs are invested in this electrification. But as was shown, we're going to have all these batteries coming out when vehicles are retired. For EV batteries, the rule of thumb is that when they're 90 % state of charge they are no longer effective and you're basically carrying around weight that is not efficient for storage on the vehicle. So, as we go to more renewable energy in the grid, we need to be able to manage it and so, there's a need for utility scale storage. There are some other technologies, but I think there's going to be a clear role for batteries. It's really looking at that reuse which would displace mining of resources to make new batteries, and therefore reduce those impacts. So, it's repurposing of batteries for utility scale, but we also need to consider materials recovery, even after utility scale storage is depleted. Dr. Curry-Nkansah added that rooftop PV in combination with repurposed batteries in ongoing. Also, companies like Honda, GM and others are bringing together used batteries to power data centers. Very active area. Key barrier in terms of the grid is that batteries are not standardized. So, trying to mix and match them will be a challenge.

Session 2a: Electronics Recycling Challenges

John Shegerian, Co-Founder and Executive Chairman, ERI

Mr. Shegerian introduced his company, and the growth they have experienced over the last 16 years of operation. ERI now has eight locations nationally and take in approximately 20 million pounds of e-waste a month. Mr. Shegerian explained that today, not only is e-waste the fastest growing waste stream in the world, but it's growing five times faster than other waste streams. It has a become a bigger problem than ever before. Mr. Shegerian argued that e-waste does not belong in the landfill, but rather when recycled correctly, represents a zero waste, zero emission CE story. He stated that most people think the product of e-waste recycling is gold bullion bars, but that is not the case at all. Rather, the major output of e-waste recycling is steel, plastic, glass, aluminum, and trace amounts of precious metals (gold, silver, palladium). Mr. Shegarian ensures that in his operation, every one of those commodities goes to reuse, gets repurposed into new products in the U.S., or elsewhere in the world, such as China, India, or other parts of SE Asia, where there is a thirst for the commodities as they build infrastructure and their economies. Finally, Mr. Shegerian spoke to the changing industry as electronics proliferate into new products and industries. Car companies are now his clients. With this change, he argues, comes opportunity.

Peter Afiuny, Executive Vice President, Urban Mining Company

Mr. Afiuny introduced the Urban Mining Company (UMC), explaining that is it the only magnet mill globally with the capability to produce high performance up-cycled magnets. UMC sources Nd-Fe-B materials from EoL channels and motor assemblies, medical devices, data storage, and wind turbine assemblies. They then harvest the Nd-Fe-B materials from the EoL products using a focused extraction methodology and utilize them in the production of new Nd-Fe-B magnets (neo-magnets). Mr. Afiuny explained that the traditional supply chain of neo-magnet materials relies on REE extraction, which are primarily located in China. But UMC's decentralized supply chain eliminates geopolitical risk factors, and the feedstock availability is strong, as displayed by the graph in Figure A5. Mr. Afiuny stated that their facility in San Marcos, Texas can produce 2000 tons/year of neo-magnets and they have plans to increase to >10,000 tons/year, representing at least 6 % of the global magnet market share.

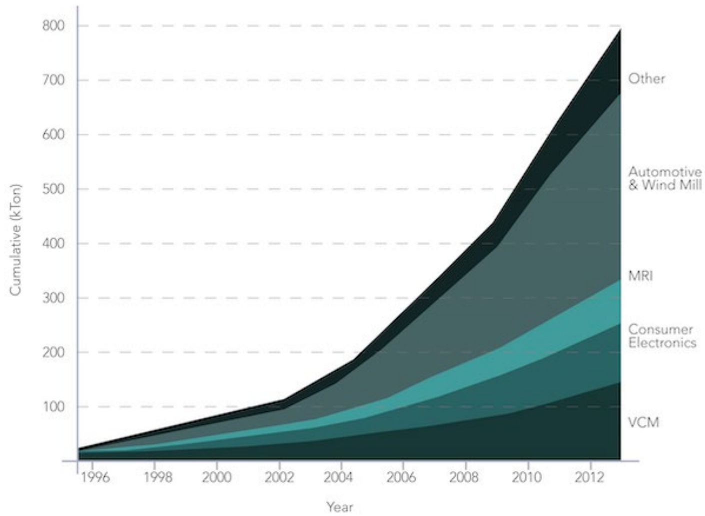


Figure A5: Estimated cumulative waste EoL feedstock of Nd-Fe-B material that is available, by sector (VCM: voice coil motor, MRI: magnetic resonance imaging)

Mr. Afiuny stated that innovation in materials science creates more complex product architectures, and the current recycling infrastructure needs improvement. He stated that rare earth materials are present in everyday electronics and are therefore critical to the global economy, yet less than 1 % of rare earth materials are recovered. This is because the current recycling infrastructure is archaic and is fueled by economics of resale markets and bulk recovery through a shredding model. Mr. Afiuny contended that shredding creates an unnatural mix of elements not found in our natural environment. Instead, he calls for a switch to a focused extraction methodology where specialized materials producers develop processes and technology to surgically extract materials from EoL and upcycle them into new products.

Julie Daugherty, Business Development Leader, Multimetco

Ms. Daugherty introduced Multimetco as the original platinum group metals smelter that pioneered catalyst smelting in the early 1980s and is now the longest running auto catalyst smelter in U.S. She briefly explained their capabilities regarding responsible data destruction, expertise in plasma arc furnace technology, and extensive U.S. and global warehouse and purchasing network. She then presented several industry challenges, which included the following:

- Constant evolution of electronics
- Skilled labor shortage
- Regulation and compliance
- Deleterious byproducts
- Increasing metal prices

The constant evolution of electronics as a particular challenge for Multimetco. This includes challenging elements such as lead, beryllium, and embedded lithium batteries (which cannot be shredded), as well as constantly changing grades. These factors change the makeup in the feed stream entering Multimetco, requiring more accurate sampling methods and more in-depth analysis of feed. Ms. Daugherty also explained the skilled labor shortage as a real challenge, as there is little automation in the industry and thus, they rely on skilled and experienced operators which is scarce due to competition from other manufacturing sectors.

George Lucas, Vice President of Sales and Business Development, Gannon & Scott

Mr. Lucas began his talk stating that there is a need for lower grade processing and shredding in bulk, as well as a need for what G&S specializes in, which is mid- to high-grade material recovery. He explained that G&S has three processes to recover precious metals: thermal reduction (incineration) of filters, resins, wipes, factory debris, and e-scrap; melting (for extremely high-grade materials) of industrial scrap, cathodes; and chemical processing and stripping. They also have laboratory services (ISO:9001 certified) to enable them to characterize their products. Mr. Lucas focused his talk on three points: impact of market prices on recycling and recovery, closed-loop recycling and how it impacts business, and the importance of data on recycling operation and processes. He provided several examples of market prices for materials, including palladium and silver from capacitors, and how they impact recovery value. Multimetco performs closed-loop services for businesses (i.e., performs the recovery process and materials return to the client) which Mr. Lucas stated is a way to mitigate market risk, reduce purchasing and cash flow requirements, avoid supply and demand delays, as well as support sustainable and responsible manufacturing and recycling. Further, he emphasized the importance of data on recycling operations and processes and gave several examples of assay results.

Julie Schoenung, Professor and Chair, Department of Materials Science and Engineering, University of California, Irvine

Dr. Schoenung introduced her research on the sustainability aspects of properties, processing, and microstructure of high-tech products, including electronics, solar panels, and batteries. She spoke about material selection from a recycling perspective and stated that a key challenge is the fact that electronic products are designed primarily on the basis of functionality and performance, coupled with costs. Product designs then dictate materials selection and manufacturing design options. As a result, electronic products rely on many components and substances with ever increasing complexity. Dr. Schoenung stated that designing for recyclability can lead to economic benefit, reduced energy demand (and associated carbon footprint), and reduced materials footprint from the strategic selection of materials, but this needs to happen early in the design process and together with decisions about upgraded product and manufacturing designs. She further explained a materials footprint as including supply chain issues, resource inputs (materials, energy, transportation), emissions and by-products (air, soil, water), occupational exposures (material hazards and toxicity), and corporate responsibility. Last, she asked how we can quantify a materials footprint and use the information to make better materials selection decisions. She presented several programs and organizations focused on measuring different aspects, including embodied energy included in LCA, hazards and toxicity included in information and labeling programs (e.g., GreenScreen), and sustainability standards (e.g., EPEAT). But she stated the need for comprehensive alternatives assessments: techniques or frameworks that analyze design parameters (functionality, performance), together with economic requirements, human health impacts (toxicity), and environmental performance (carbon and materials footprint).

Speaker Q&A

Questions of the panel included the following:

- Is the growth of the e-waste stream expected to continue?

  Response (paraphrased): The panelists answered in affirmation, stating that at least 22,000 new SKUs (stock-keeping units, i.e., new products) a year are presented at the annual Consumer Electronics Show, a convention in which manufacturers display new models of electronics being put on the market. The panelists agreed innovation and gadgets are scaling up.

- What are the biggest barriers to material recovery from electronics?

  Response (paraphrased): The transition between lab scale and commercialization is a key barrier. Recycling technology developers are challenged to prove the viability of their recovery technology from an economic standpoint at a commercial scale. Bringing recovery operations to commercial scale usually only happens under a viable business case that is generated either in fundraising through public or private means. But most investors are resistant to giving money to R&D projects that have not had at least some sort of a result at a commercial scale. It has to do with process scalability within the R&D communities. Additionally, panelists identified consumer education as a second barrier to material recovery. They stated that consumers are unsure of how or where to recycle their electronic products responsibly. Thus, consumer education is a major gap.

- A question was posed to Ms. Daugherty about whether Multimetco creates training programs with local universities.

  Response (paraphrased): They are looking into it, but university and other educational programs do not necessarily train for processing of older sort of furnace operations and training is often performed in practice instead. In other words, not a lot of young people coming out of college are trained to work in Multimetco or G&S type facilities, nor are they necessarily interested in working in the messier (low-tech) environment, and this is a challenge going forward.

Slido Discussion Session

Slido was used to solicit responses to questions on the session topic. Slido questions and select responses are as follow:

- What is your role in electronics recycling? (multiple choice question, percentage represents respondent breakdown):

  Government: 24 %
  Producer/Manufacturer: 15 %
  Recycler: 15 %
  Researcher: 36 %
  Reuse/Repair: 0 %
  Industry Organization: 6 %
  Other: 3 %

- What does a bad day look like at a recycling facility?

  The top five responses (based on participant upvoting) included: contaminated stream; injury; battery fire; stolen material from secure area; and no material to process.

- To what extent does lack of appropriate data impede your ability to be more circular? (Rating question where 1 = not impeded by lack of data, 5 = very impeded by lack of data)

  1: 3 %
  2: 7 %
  3: 3 %
  4: 33 %
  5: 53 %

- What specific data would you benefit from? (e.g., LCA data for products, recycling operations and processes, materials content of products, etc.)

The top five responses included: material content of products on a durable label; standardization of components; transparency from manufacturers; reuse market potential; and LCA data.

- What standards, either documentary or reference materials, would enhance recycling of electronics?

  The top five responses included: R2 standard version 3 (the Sustainable Electronics Reuse & Recycling standard); standards need to be more specific about how activities will be completed, the guidelines are too broad; recyclers downstream transparency; EERA (European Electronics Recyclers Association) type standard that certifies that electronic materials are recycled properly in a sustainable way; and standards for providing full material declaration on the product (via QR or bar code) so recyclers can know what they are managing.

- What will it take to overcome the social, economic, and political barriers to recycling?

  The top five responses included: National or global standards rather than piece work standards per geo or state; education; commitment from senior government leaders; better design; and global economic incentives.

- Are there other challenges to electronics recycling that have not yet been discussed in this session?

  The top five responses included: human behavior; collection and transportation; what if the electronics products do not use metals anymore; bad actors; and Recycling Destruction Certificate.

Session 2b: Battery Recycling Challenges

Jean-Christophe Lambert, Business Development Manager, Lithion Recycling

Mr. Lambert introduced Lithion Recycling explaining that, with support from their sister company, Seneca, they developed a technology that now recycles 95 % of battery components. They recycle all types of LIBs including from cars, buses, e-bikes, phones, etc. Their process begins with a shredding operation to separate the content of cathode and anode (known in the market as black mass) from the foils of the cathode and anode and the casings of the modules. This process is fully automated and does not require battery discharge. The black mass recovery is greater than 98 % and undergoes a hydrometallurgical process in which metal salts are produced that go back into the precursor market for cathode manufacturing. Recycled products from Lithion include cobalt, nickel, manganese sulphates, lithium carbonate, and graphite. Mr. Lambert explained that Lithion employs hydrometallurgy (as opposed to other recovery methods) first and foremost because of its ability to produce battery grade materials that meet the necessary purities to return them to the LIB market, as well as the decreased environmental footprint of the process. Lithion operates a ‘hub and spoke’ model of collection and processing, where batteries are collected from distributed (often rural) locations and brought to a centralized facility (i.e., the hub) for processing. Mr. Lambert explained that battery transport is a significant challenge, given the safety concerns associated with battery explosivity and fires. He stated that it is much easier to make a technology move than a battery, and Lithion is therefore working to deploy their recovery technology to limit the transportation of LIBs. Additionally, he noted the challenge of the process development path of hydrometallurgical technology, in which risks related to laboratory development, bench scale research, and pilot scale must all be accounted for.

Todd Coy, Executive Vice President, KBI Recycling

Mr. Coy discussed the history of KBI Recycling which has grown and adapted to now include warehousing new battery products and supporting direct-to-dealer services (e.g., if a battery is removed from a vehicle, KBI sends a new battery replacement, and recovers the replaced battery). Replaced batteries are consolidated with others and sent to KBI's partner company, Retrieve Technologies who specializes in LIB recycling, and has two facilities, one in British Columbia, Canada and the other in Lancaster, Ohio, the latter commissioned through a U.S. Department of Energy (DoE) grant supporting U.S. battery recycling capacity in advance of the growing EV market. Retrieve Technologies' recycling process involves shredders, screens, and hydrometallurgical material separation technologies to liberate active cathode materials from batteries. In terms of battery recycling, Mr. Coy pointed out that there has been a shift in the role and responsibility of recyclers and the activities they perform to support the industry: their role has expanded to include subject matter expertise in areas such as transportation regulation, environmental regulation, as well as packaging solutions (especially related to damaged and defective batteries which are increasing in the waste stream). He mentioned that the LIB supply chain is not integrated like that of lead acid batteries, where manufacturers are also engaged in collection and recycling activities, a model Mr. Coy supports.

Linda Gaines, Chief Scientist, Argonne National Laboratory

Dr. Gaines introduced the ReCell Center which was started approximately two year ago by the DoE as part of a plan to reduce U.S. dependence on critical materials for batteries. The ReCell Center is a collaboration of three national laboratories and three universities with the mission of decreasing the cost of recycling lithium-ion batteries to ensure future supply of critical materials and decrease energy usage compared to raw material production. Dr. Gaines explained the three primary battery recycling methods: 1) pyrometallurgy, the use of high heat to essentially treat the battery material as ore, producing a mixed metal crystal, 2) hydrometallurgy, the process of dissolving the battery materials in strong acids enabling the recovery battery precursor salts (metal salts), and 3) direct recycling, retaining the complex crystal structure of the cathode material (black mass) for use directly back into batteries. The ReCell Center is focused on the third method as it involves fewer steps, requires less energy, and recovers more materials. See Figure A6 for the role of the different methods in the CE. Dr. Gaines explained that even as the content of high-value materials (namely cobalt) are decreased in LIB cathodes, the cathode materials are still more valuable than their constituent elements. Additionally, not separating the cathode constituents retains potentially harmful elements (e.g., fluorine), that would otherwise require specific handling in the waste stream. Dr. Gaines mentioned a lifecycle assessment comparing the three recycling processes (pyrometallurgy, hydrometallurgy, and direct recycling) and found direct recycling has the lowest impacts in essentially all the categories (energy consumption, water consumption, GHG emissions, SO_x emissions).

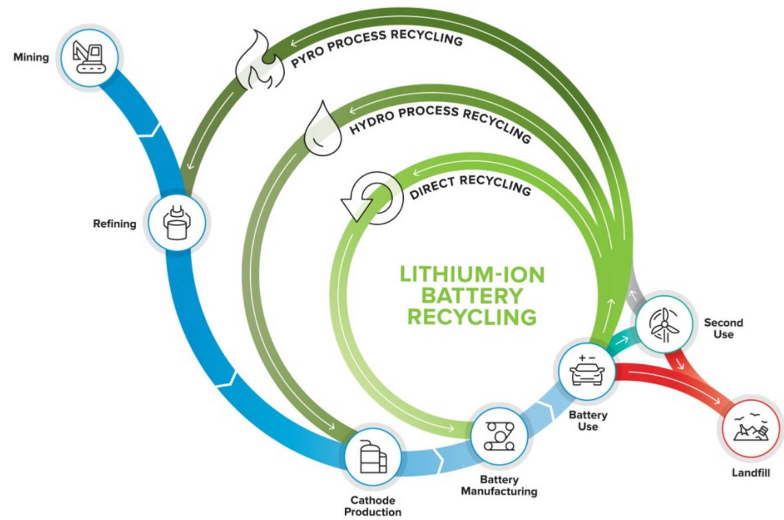


Figure A6: LIB Lifecycle: Direct recycling minimizes steps back to use

Stephanie Shaw, Technical Executive, Electric Power Research Institute

Dr. Shaw spoke about the recovery and recycling of batteries used for utility energy storage. She presented an evolution of battery recycling challenges which included the following:

- EoL module volume awareness
- Recycling approaches uneconomical and not easily managed
- Decommissioning costs are large and unexpected
- No infrastructure, policy, or incentive support to motivate the fledgling industry
- Widespread manufacturer, vendor, utility, R&D awareness of EoL need
- Material supply security, critical materials, and market benefits are strong motivators
- Many more vendors, though clarity needed on processes, costs, experience
- More economical, more easily managed; needs refinement & transparency
- Decommissioning costs expected, but highly uncertain
- Decommissioning requirements and best practices non-existent

She discussed the reality that decommissioning plans for energy storage facilities are generally uncommon, highly varied, and on different bases. She argued that EoL obligations are not fully understood and accounted for by most of the developers and operators in this space. EPRI's efforts are three-fold: understand the available options and cost ranges for various EoL services; document decommissioning case studies and best practices experienced by others; and participate in fundamental R&D to help improve recycling and second use options to facilitate a broader range of CE participation. Dr. Shaw stated that utilities are frequently asked about the potential for use of second life EV batteries in stationary applications, particularly for large scale utility deployments. Utilities in general are eager to understand options for second life but question whether second life at the utility scale makes sense compared to alternative applications. Further, there is currently a lack of accurate/certified performance financial data, which hampers an assessment of the feasibility. She discussed four points when considering battery second life for grid applications before recycling:

1. Cost: new LIB costs continuing to decrease, also would insurance costs be higher?
2. Re-certification: Original equipment manufacturer (OEM) versus remanufacturer liability, statistical risk data needed including malfunction rates and types
3. Processing and preparation: diagnostics needed in addition to product specific information to compare performance and lifetime, this reduces vendor margins
4. Operations and lifetime: include product-specific information in battery management system (BMS) such as maintenance and perhaps even a life prediction

Dr. Shaw stated that currently, given the lack of information available, it would be a challenge for a newly designed facility for second life batteries to compete in a procurement process based on business case metrics and questions about their reliability. Virgin systems, on the other hand, may have more efficient performance and lower masses of critical materials which may make them easier to recycle at EoL due to the rapidly advancing R&D. At this point, it may be that other applications, such as EV charging stations, may be the best use of second life modules.

Callie Babbitt, Associate Professor, Golisano Institute for Sustainability, Rochester Institute of Technology

Dr. Babbitt introduced her research on the broad topic of systems thinking for sustainability, in which she as focused on multiple product streams including LIBs. She discussed the complex supply chain of battery materials, particularly for cobalt which is produced primarily as a byproduct of copper and nickel mining and is largely centralized in the Democratic Republic of Congo where concerns about child labor have arisen. Dr. Babbitt stated that closed-loop recovery can help alleviate these social, environmental, and economic risks. She discussed the trends of electronic device sales, noting that the biggest growth is in mobile devices, i.e., battery-containing electronics. However, she then presented a graph (Figure A7) of the projections of EV battery packs entering the waste stream over time which will likely surpass the number LIBs in e-waste within the next decade. This will necessitate a shift in collection and logistics of recycling processes.

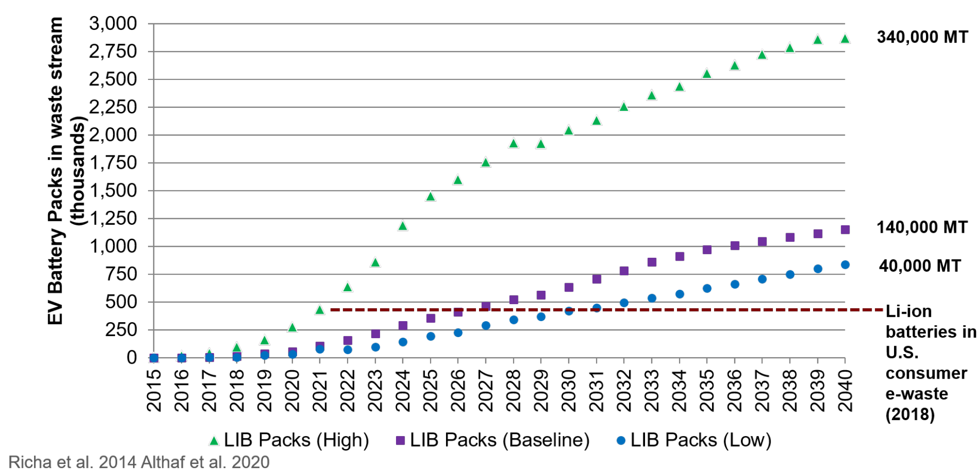


Figure A7: EV battery packs in the waste stream: Batteries in electronics will soon pale in comparison to those in EVs

Dr. Babbitt explained that closed-loop recovery is limited by dispersion and design: more products are increasingly embedded with a battery while the material content (e.g., cobalt) is decreasing. As a result, more products must be processed to recover the material. She also mentioned the role of design, and that products are not currently designed for easy battery recovery and thus the process is labor intensive. Dr. Babbitt said that solutions must be evaluated on a lifecycle basis and potential policy considerations during each phase could include the following:

- Production: material selection, design for EoL
- Use: Driving and charging to minimize degradation
- Collection: Extended producer responsibility (EPR) and risk, collection programs
- Reuse/Cascaded use: better testing guidelines, policy inclusion of cascaded use applications (i.e., the maximization of resource effectiveness in different applications), economic incentives for reuse/cascaded use
- Recycling: Labeling/identification, recycling efficiency improvement
- Landfill: landfill ban

Speaker Q&A

Questions of the panel included the following:

- Is direct recycling a specific process or any combination of processes such as combination of mechanical and hydrometallurgy?

  Response (paraphrased): Dr. Gaines responded that direct recycling is a series of processes that are meant to get the individual components back out of the cell. The first step would be shredding, followed by a series of processes to separate the nano materials as well as recover the electrolyte. There is a whole series of unit processes that are including in the research. One of the interesting tests right now is to try to figure out which of the potential processes in each step will be the most efficient.

- What are the primary transportation challenges that increase costs and hinder recycling?

  Response (paraphrased): The material is classified as a Class 9 hazardous material due to potential safety concerns (e.g., ignitability) which requires specific handling and therefore higher transportation costs. Increased coordination is necessary in the determination of best-case solutions for each battery and where batteries end up at EoL.

- How can NIST help: are there needs for standard reference materials or chemical agents that NIST can provide?

  Response (paraphrased): Minimum performance standards would be useful to ensure buyers of the quality and expected performance of a recycled or second-use battery (as well as other products).

- To Dr. Gaines: When will the technology reach commercial scale?

  Response (paraphrased): They hope to have something ready at bench-scale in about a year (the end of their three-year project), and she would assume it would take about five years for the industry to design, build, and operationalize a pilot plant.

- Where in the battery system do you think we should take priority action in order to enhance future circularity?

  Response (paraphrased): There has not been enough attention at the early stage. We are trying to meet the objective of driving down costs by lowering the cobalt concentration. That happened downstream on the recycling side. That means recyclers want to think about other ways of recovering materials that are not just based on the commodity value or the cobalt commodity value. Another consideration is the design infrastructure for data, i.e., a battery management system (BMS) which enables the ability to transfer data about the operating status, history, and resulting quality of a battery that supports reuse and recycling decision-making.

- Why is the BMS necessary for reuse if you have to test the cells and modules prior to reintegration?

  Response (paraphrased): The aim to create a data-rich environment across the life of the battery. A lot of work is going on in advanced diagnostics and predicting asset health management. The ability to recover data about use and reuse that support additional diagnostics that might come along.

- Lead-acid batteries are very standardized, will LIBs ever be?

  Response (paraphrased): There is reluctance to standardize in the U.S. If there were a standard size and shape of battery modules and cells that would make the disassembly process possible to do robotically rather than needing to shred. If battery chemistries were standardized, we would not have to worry about separating different materials within the recycling process. Any kind of standardization would simplify the recycling process tremendously. Has been mandated to some extent in China.

- What are other challenges to battery recycling that have not yet been discussed?

  Response (paraphrased): Right now, there is a robust recycling system in North America, which essentially is producing a black mass. The next step that must be done is converting it into the precursor materials. The challenges there are evolving, particularly due to the volume and material that is available. To introduce material back into the supply chain requires consistent quality and quantity. While the technology is available, the challenge is reaching the necessary volume given the evolving recycling stream.

Slido Discussion Session

Slido was used to solicit responses to questions on the session topic. Slido questions and select responses are as follow:

- What is your role in battery recycling? (multiple choice question, percentage represents respondent breakdown)

  Government: 20 %
  Producer/Manufacturer: 27 %
  Recycler: 7 %
  Researcher: 27 %
  Reuse/Repair: 0 %
  Industry Organization: 13 %
  Other: 7 %

- What does a bad day look like at a recycling facility?

  The top five responses included: fire; recordable injury; not enough batteries to recycle; contaminants; and market for materials tanks.

- How feasible is a second life for batteries as opposed to immediate recycling? (Rating question where 1 = not at all feasible, 5 = very feasible)

    1: 0 %
    2: 22 %
    3: 43 %
    4: 17 %
    5: 17 %

- To what extent does lack of appropriate data impede your ability to be more circular? (Rating question where 1 = not impeded by lack of data, 5 = very impeded by lack of data)

    1: 0 %
    2: 29 %
    3: 10 %
    4: 33 %
    5: 29 %

- What specific data would you benefit from?

  The top five responses included: materials content of battery; remaining health after first life; refurbished battery performance testing; cost-revenue data for different scenarios; and downstream information and markets.

- What standards, either documentary or reference materials, would enhance recycling of batteries?

  The top five responses included: performance standards for recycled materials; material purity for electrode use; minimum performance standards; NIST Best Practice Guides on characterization for verifying performance; and non-proprietary evaluation methods of battery health.

- What will it take to overcome the social, economic, and political barriers to recycling?

  The top five responses included: design for circularity; consumer education; incentives for recycling; market pull and policy push; and demonstration of safe economic process.

- Are there other challenges to battery recycling that have not yet been discussed in this session? (e.g., prevention of fire hazard)

  The top five responses included: Standardization (it's a wild west now); materials export and trade policy; safety protocols at point of disassembly; low collection rate; and reuse limited by cell degradation need better data for degradation - remaining lifetime and diagnostics.

Session 2c: Solar Panel Recycling Challenges

Ricky Sinha, Senior Scientist, First Solar

Dr. Sinha spoke largely to the need to standardize high-value PV recycling. He stated that current PV recycling is bulk recycling, which is primarily focused on aluminum, cables, and glass recovery. The challenge is to ensure recovery of semiconductor and other metals (high-value recycling). High-value PV recycling is important because of the inclusion of environmentally sensitive materials in PV panels (e.g., Pb, Cd, In, Se, Ag) and because it provides socio-economic and environmental benefits such as job creation, minimized life cycle impacts, as well as reclaimed valuable and energy-intensive materials. According to Dr. Sinha, recoverable value of high-value recycling could exceed $15 billion by 2050.

Dr. Sinha described First Solar's module recycling process in which they perform both bulk and high-value recycling and recover more than 90 % of semiconductor material and ~90 % of glass.

Dr. Sinha explained two approaches to promote and standardize high-value recycling: top-down regulation and bottom-up market pull. He discussed standards and recycling targets for PV modules in the U.S. as well as the E.U. Specifically, Dr. Sinha discussed E.U. WEEE standards which set a recycling target of 80 % by weight. However, recycling bulk materials alone, e.g., aluminum and glass, meets that requirement. He then talked about CENELEC (the European Committee for Electrotechnical Standardization) supplemental WEEE standards which strive to move the industry towards more high-value recycling and has specific requirements for how much lead, cadmium, and selenium can be in the output glass to motivate the recovery of those metals. In the U.S. there is no mandatory recycling of PV panels at the federal level, however at the state level California has included PV modules in their universal waste rules, which is expected to increase PV recycling (vs. landfilling) in the state.

In terms of bottom-up approaches, the market is partly driven by programs like the EPEAT ecolabel which registers products that are the leaders in the respective industries on sustainability. A new category in EPEAT focuses on PV modules and inverters and specifies material recovery targets (Criterion 9.1.3) and recycled content in product (Criterion 6.1.2). Dr. Sinha also pointed out the Sustainable Electronics Reuse & Recycling standard (SERI R2) in which the inclusion of PV panels is under consideration. The R2 standard is intended to help recyclers have safe and high yield recycling practices.

Kristina Whitney, Chief Financial Officer, Recycle PV Solar

Ms. Whitney opened her talk with general facts about the solar industry. She stated that 140,000 solar panels are installed every day in the U.S., which is roughly 3500 tons. Total installed solar PV in the U.S. is now more than 65 GW, representing <5 million tons. These panels are mainly imported to the U.S. Europe recycles about 95 % of all solar, whereas the U.S. recycles approximately 10 %. She indicates that this is because there is no comprehensive solar recycling infrastructure in the U.S., and there are few government programs supporting EoL of solar. This represents a growing problem.

Ms. Whitney stated that PV installation is growing rapidly, but within 10 years, as much PV will be decommissioned as installed. Reasons for decommissioning include manufacturing defects before install, breakages in transit or installation, recalls due to performance, damage due to severe weather, and repowering because of tax incentives. She explained that while there is value in the materials of solar panels, the economics of recycling does not make sense at this time. Currently, the cost to process a solar panel in the U.S. is between $15-$45, whereas in Europe the price is $0.70 per panel which includes collection, transport, and processing. Ms. Whitney shares that a U.S. national solar recycling program could be funded today with $0.01 cent per watt charged to end users, which is about $2 to $4 per panel. The goal of her organization is to drop prices to $0.50 to $0.70 per panel as volume, logistics, policy, and infrastructure matures. Ms. Whitney identified several industries that have managed their own processes to sustainably recycling their manufactured waste, in which they charge a small upfront fee at purchase to cover the cost of recycling. These industries include car batteries, car tires, flat screen TVs, refrigerators, mattresses, cans, bottles, and florescent lamps. She argues that the solar industry should follow a similar approach.

Garvin Heath, Senior Scientist, National Renewable Energy Laboratory

Dr. Heath discussed a recent publication of a roadmap for PV recycling. He began by describing challenges to reuse and repair, which include business-model, economic, and regulatory challenges. Reuse and resale require inspection, repair (as necessary and if possible), testing, and potentially recertification for safety and performance. Manufacturers will need to maintain replacement components for long module lifetimes and reused models may not provide as much economic value to system owners, even at a lower cost, compared to new models. Dr. Heath stated that all modules reach EoL at some time and therefore, most focus for a PV CE is on recycling.

Dr. Heath explained the authors' R&D recommendations for crystalline silicon (Si) module recycling. The authors focused on Si recovery based on the results of a TEA which concluded that Si recovery has the highest value increase potential if high purity Si can be recovered. He noted that metallurgical-grade silicon is 98 % pure and costs approximately 2 USD/kg, whereas solar-grade silicon (6N-11N) costs up to 30 USD/kg. Additionally, Si recovery has a large potential environmental benefit as silicon wafers account for nearly half or more of the embodied energy and 50-66 % of the climate change footprint of a c-Si module.

Dr. Heath (and authors) recommend a deemphasizing R&D on recycling processes designed to recover intact silicon wafers. While recovery of intact wafers has been demonstrated at laboratory scale, numerous barriers remain to achieve dependable, large-scale intact wafer recovery at necessary purity levels. Dr. Heath listed several of these barriers which include the following: cells are often cracked at EoL; cells are becoming thinner, leading to increased risk of cracking over time; the question of whether intact wafers from older modules will meet current requirements such as efficiencies and lifetimes, changes in cell form factor, and reduced impurity tolerances. Finally, current solar silicon manufacturing processes are designed based on virgin polysilicon, and broken cell fragments may not be useable as a replacement.

Dr. Heath discussed the need to design silicon purification and crystal growth processes for recovered silicon to increase circularity of solar panels. He noted that recovered silicon could become an important source to meet the growing demand, yet competition with an improving virgin feedstock industry will remain. He stated that there is no physical reason why the high-grade silicon embodied in solar cells cannot be reformed into solar-grade silicon, but that the challenge and research opportunity are in re-optimizing existing manufacturing processes or developing new processes for the impurity profile and physical form of recovered silicon. According to Dr. Heath, impurity control is paramount throughout the solar Si supply chain as the performance of Si solar cells depends strongly on impurities and, furthermore, the entire cell and module fabrication process redistributes impurities and changes their chemical bonding states, which affects cell performance.

He further recommended investigating characteristics of recovered silicon to inform it's return to the silicon value chain. This requires precise and complete characterization of impurity profiles, which is yet incomplete in industry. Dr. Heath explained that industry requires low tolerance in impurity profiles, specifying that solar-grade silicon is at least 6N (99.9999 % pure), and the trend is toward higher purity, with 11N now used. The highest-grade virgin feedstock is expected to have transition metal impurities on the order of one part per billion. Recovered silicon is likely to have an impurity profile different from that of virgin because of several factors, including dopant diffusion (e.g., boron, aluminum, phosphorous) during high-temperature cell junction formation, contact formation (from using silver pastes), soldering processes, as well as contamination that occurs during module operation and subsequently during recycling such as sodium migration from glass to Si. Dr. Heath noted that the cost to achieve higher purity should be balanced against prices offered by different industries: it should be questioned whether solar is the right or best market.

Regarding recycling processes, Dr. Heath recommends using anticipatory, systems-based analytical tools such as TEA and LCA to consider tradeoffs of process steps and inform process design. He stated that each recycling process step, considered alone and in combination, can affect the yield, purity, and/or physical form of recovered materials which influences the overall value. The choice of process steps also impacts the capital infrastructure requirements, amount of waste generation, and use of chemicals and energy for recovery. He noted that both TEA and LCA have been applied to PV recycling, but have not yet been integrated and applied to recycling systems. He further recommended the monitoring of PV module changes and designing recycling infrastructure to be adaptable to variable module inputs. PV module designs change frequently, whereas recycling infrastructure is capital-intensive and long-lived. As PV recycling infrastructure is developed, it should be designed to treat the widest range of module designs, be adaptable to variable designs, or be designed to process specific module designs which are most prevalent in the region. Dr. Heath recommends partnership among PV technology manufacturers and the recycling industry to support effective design and recycling of PV modules.

Last, Dr. Heath recommended a focus on policy, logistics, and data needs to support PV recycling. In the policy context, waste classification as non-hazardous or hazardous impacts the allowable options for the handling, transport, and disposal of modules. Such classification often depends on toxicity testing, where the sampling method, sampling location, and lab-to-lab variability affect the hazardous waste determination. Logistically, the scale and location of recycling facilities and sorting operations need to be considered, such as centralized versus decentralized facilities. Decentralized mobile sorting or initial recycling facilities at a PV installation site reduces burdens of transporting bulky and heavy EoL models. Dr. Heath gave the example that the number of modules in a container can increase by a factor of seven when frames and junction boxes are removed. Regarding data needs, Dr. Heath called for publicly available data on the rates and modules reaching EoL to help allocate capital. Such data such should include modules reaching EoL "naturally" and due to extreme weather, breakage, and failure modes, as well as regularly updated waste predictions, ideally at subnational resolution.

Cara Libby, Principal Technical Leader, Electric Power Research Institute

Ms. Libby discussed four key challenges to a CE for solar panels. The first is the delayed and uncertain EoL module supply, in which extensive investment in recycling R&D and infrastructure development is delayed due to the lag between now and when substantial amounts of modules will reach EoL. She provided a graph (Figure A8) displaying projection of annual volumes of EoL modules by region. She noted that infrastructure planning investment decisions require detailed EoL projections at the state or finer resolutions.

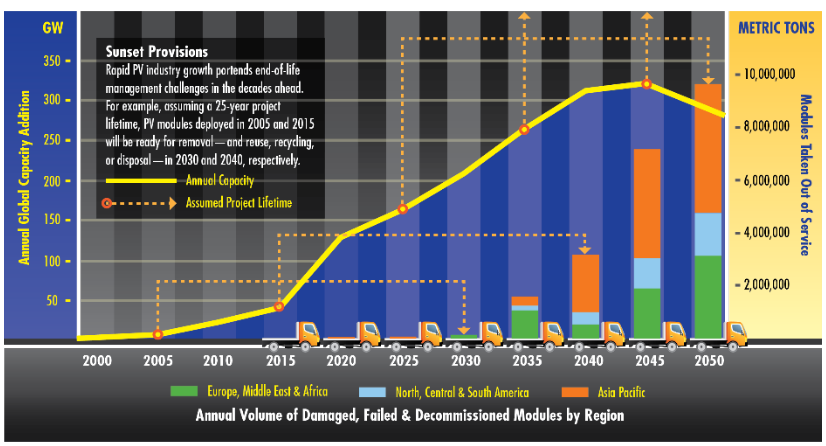


Figure A8: Annual volume of damaged, failed, and decommissioned modules by region

The second challenge Ms. Libby discussed pertained to the high and uncertain module recycling costs. She stated that recycling c-Si modules currently costs between $10-$30 per module (based on anecdotal evidence), whereas landfilling modules is $0.50-$1.80/module and hazardous waste disposal starts at $3.60/module. According to Ms. Libby, module reuse is the most attractive option in the U.S., economically as well as environmentally, and may provide the time needed for lower-cost recycling to emerge. Module refurbishment and remanufacture are emerging options with unknown costs.

The third challenge Ms. Libby discussed was the need for new, high-value recycling processes. Most current PV recycling takes place on existing glass recycling lines and is done on a batch basis due to the low module volumes. The value proposition for recycling is expected to improve through recovery of valuable materials such as silver, copper, and high-purity silicon. However, the environmental impacts associated with the higher energy demand of high-value recovery processes must be considered.

The fourth challenge Ms. Libby discussed is that of uncertain regulations. Currently, there are no U.S. federal policies, and state-level regulations vary with respect to PV recovery and recycling. Ms. Libby stated that PV recycling today is not economical on its own so regulations may be necessary to drive recycling. She also proposed whether regulatory exemptions might improve environmental sustainability metrics if applied to PV.

Meng Tao, Professor, Arizona State University

Professor Tao discussed the current recycling process, module reuse, and future processing for material extraction and reuse. Current recycling involves bulky material extraction which relies on purely physical methods for removal of the junction box to recover copper, removal of the aluminum frame to recover the aluminum, and module shredding to recover the glass. Current recycling costs approximately $30/module, but recovery is ~$3/module.

According to Dr. Tao, module reuse can generate about $20/module, and while there will be hundreds of gigawatts per year of decommissioned modules, the challenge is finding buyers. The process for reuse includes cleaning modules to remove dust and deposits, visual inspection for damage, and module recertification through an efficiency test.

Dr. Tao proposed a two-step process for future module recycling: module recycling followed by cell recycling. Module recycling involves the same physical methods used currently to recover copper and aluminum, but the cells are then recycled using chemical methods to extract Si from the glass pane. Dr. Tao explained that metals such as Ag, Cu, Pb, and Sn, can be leached off Si cells and then the extracted from the leachate with electrowinning. After removal of the Al and SiN_x, a Si wafer with 99.995 % purity can be recovered. Dr. Tao estimates the revenue to be ~$10/module (~50 % of which comes from recovered Ag), three times higher than that of current recycling processes. He discussed the revenue breakdown by material recovered from a 60-cell Aluminum Back Surface Field (Al-BSF) module (Table A1).

Table A1: Revenue by Material Extracted from 60-Cell Al-BSF PV Module

Material	% Recovery	Weight	Price ($/kg)	Value	% Total
Glass	100	13.5 kg	0.10	$1.35	14.1
Al	100	1.83 kg	0.84	$1.53	15.9
Polymers	0	1.18 kg		0	0
Si	90	0.56 kg	1.50	$0.93	9.7
Ag	100	6 g	818.61	$4.91	51.1
Cu	100	0.11 kg	6.79	$0.75	7.8
Pb	100	18.3 g	1.28	$0.02	0.2
Sn	100	21.9 g	4.96	$0.11	1.1
Total				$9.60	100

*Prices as of 1/12/2021

Dr. Tao explained the equipment needed for such high-value recovery, identifying two companies, NPC Incorporated in Japan and TG Companies in Arizona, who perform mechanical and chemical processing, respectively. For example, NPC Incorporated has the capability to remove and recover the junction box and aluminum frame and extract cells from modules, and TG Companies then uses pyrolysis of polymers on cells to recover Ag and 4N Si. Dr. Tao noted that recovery of Pb, Sn, and Cu are expected to be added to the process. The NPC tool can process ~100,000 modules/year and generates roughly $300,000/year in revenue (~$3/module) whereas the TG tool can also process 100,000 modules/year and generates ~$650,000/year in additional revenue. According to Dr. Tao, the latter experiences a better return on investment, due to the reality that metal recovery is the only profitable part of silicon module recycling.

Evelyn Butler, Vice President of Technical Services, Solar Energy Industries Association

Ms. Butler introduced her organization, its members, and their recently published Roadmap for Building the Solar+ Economy. She further discussed the SEIA's EoL management and PV recycling initiative which aims to work proactively to develop EoL solutions, collaborate with stakeholders, and build reuse and recycling resources. Ms. Butler presented several challenge and opportunities regarding design, reuse, refurbishment and resale, and recycling of PV panels, which are presented in Table A2.

Table A2: Challenges and Opportunities for a CE for PV Modules

Design & Manufacture	Reuse	Refurbishment & Resale	Recycle
- Solutions for manufacturing scrap - Design innovation for ease of reuse, refurbishment, or recycling - Work with suppliers to improve purity of recovered materials	- Create and prioritize reuse above other channels to ensure viable product is utilized - Expand beyond off-grid or charitable / second-market solutions - Potential conflicts with state waste regulations	- Identify treatments that don't affect module certification - Minimize / eliminate expensive retesting - Training, staffing - Codes and standards	- Develop collection in key markets - Minimize costs to encourage recycling - R&D PV recycling equipment to maximize material recovery - Maximize communication to minimize environmental impacts

Ms. Butler explained that most waste PV material is derived from manufacturing scrap, warranty-related returns, modules broken during logistics or handling, extreme weather events, and technology upgrades. She discussed her organization's PV Recycling Program which aims to identify organizations and recyclers across the U.S. and to pair service providers with manufacturers as well as developers and installers to support EoL solutions as well as collect data pertaining to weight and volume of EoL modules. Ms. Butler also discussed recent development in state policies including financial insurance method development for solar in North Carolina and PV modules classified as universal waste.

Speaker Q&A

Questions of the panel included the following:

- Is the current recycling in the US focused on the commercial sector or residential?

  Response (paraphrased): Ms. Butler responded that we're seeing it in all applications; commercial, residential, and utility scale. Dr. Heath also noted that a vast majority of mass and volume of PV is that which was intended for or used in the utility scale markets. Dr. Tao added that someone must pay for it. If someone has 10-20 panels on their roof it's cheaper for them to landfill than pay $1000s to recycle. But utilities have public image to worry about. It is not possible to put 20,000 modules in landfill. Ms. Whitney stated that the issue isn't where they are coming from, it's the cost. It's much cheaper to landfill than recycle, but if we push for a national program, more like a bottle bill, it'll kick start a program and we won't see the problems we're seeing today.

- Directed to Dr. Tao: Why is the TG Company's recycling process more profitable than the other? Also, will it become increasingly economically viable, or will the decreasing amounts of silver counteract that?

  Response (paraphrased): Dr. Tao responded that TG Company is more profitable because it focuses on cell recycling, most of high value silver and silicon is in the cell. Silver is a big issue. From a recycling perspective, there are two scenarios: either the module contains a lot of silver and I recover it and generate a lot of revenue, or it has no silver and I don't even have to worry about it. The worst-case scenario is if you keep decreasing silver content, so you have intrinsic cost to recover silver, so there's a point when the revenue doesn't match the cost. NPC does not do the full recovery process.

- Refurbishing – any data on what fraction of modules that come in for evaluation meet the criteria to go back out?

  Response (paraphrased): Dr. Tao responded, saying he doesn't have a number. A couple of companies are doing it, in Japan and the U.S. Don't even take the modules down, just do it in the field. Ms. Whitney added that older panels are much more refurbishable. Newer ones break more readily because the easier, glass is thinner. Older units have more silver, higher value.

- What technological advancements will be required to take recycled materials from solar panels and reuse them in solar panels or other applications? What are the material requirements or metrics purity defects, performance, etc.

  Response (paraphrased): Dr. Heath responded recommending his paper in Nature Energy. Ms. Whitney added that their partners PV Cycle in Europe are already doing the processing and recycling of PV panels and they are doing it here. So, the technology exists. But we need some programs like a bottle bill to make it a sustainable process. Dr. Tao stated that the metals can be recovered and reused. They have 99% purity and that can be sold directly onto the commodity market. The difficulty is the silicon, which must be extremely pure to be reused in solar industry. Have to have a stable supply, stable quality. Dr. Sinha also added that glass is not currently getting back into the solar supply chain. If we had higher purity it could be reused in PV modules.

Slido Discussion Session

Slido was used to solicit responses to questions on the session topic. Slido questions and select responses are as follow:

- What is your role in solar panel recycling? (multiple choice question, percentage represents respondent breakdown)

  Government: 29 %
  Producer/Manufacturer: 6 %
  Recycler: 12 %
  Researcher: 47 %
  Industry Organization: 6 %

- What does a bad day look like at a recycling facility?

  The top five responses included: lead exposure; too much material and not enough markets; equipment down; fire; and too many different types of modules to process.

- What specific data would you benefit from?

  The top five responses included: accurate list of PV recyclers -- not resellers or brokers -- in the USA, the lists I've seen are really bad; location of recycling facilities and logistics information; weight fraction of materials in modules of different vintage, technology and manufacturer; secondary market requirements for materials and market value; and inventory and process data for recycling.

- What standards, either documentary or reference materials, would enhance recycling of solar panels?

  The top five responses included: prohibit solar panel disposal in dumps; regulatory compliance checklist for handling, transport, storage; purity or amount of material required (cost efficient) to recycle; material composition (like an ingredients list), even if generalized; and manufacturing standards that would support reuse/refurbishment/recycling, this could include e.g., fasteners/adhesives.

- What will it take to overcome the social, economic, and political barriers to recycling?

  The top five responses included: government policy; education; acceptance of recycling as a cost of doing business; incentives to encourage / require recycling and penalties to discourage landfilling; and it's more economic than anything else - the intrinsic values of the PV modules continue to decrease as the cost to process/recycle them increases and the barriers to doing so also increase.

Session 3: Boundary-Spanning Tools to Support a Circular Economy

John Glaser, Research Scientist, US Environmental Protection Agency

Dr. Glaser presented the EPA's Alternatives for Disposition of Electronics Planning Tool (ADEPT), which is a computational tool to evaluate used electronic flows for the U.S. He noted that in 2014 American's generated 16.6 kg/capita of e-waste, the treatment of which is largely dependent on state regulations which differ across the U.S. (about half of U.S. states have e-waste regulations). E-waste processed domestically generally either goes to landfill, incineration, or is recycled. There is also an export market for e-waste, in which it is sent to development countries where informal recycling practices including open burning, acid extraction, and land disposal may be practices, but Dr. Glaser indicated that this has been decreasing over time.

Dr. Glaser stated that the objectives of the ADEPT tool included the following:

- look at flow of materials and associated waste (historic, current, and potential future)
- assess potential effects of the state level electronics recycling requirements
- evaluate any existing methods for evaluating and tracking used electronics
- develop information-based method for estimating the flow of used electronics and e-waste within the US using data generated at the state level
- estimates inform formulation of e-waste policies, management of take-back programs, and policy implementation monitoring

In their approach, his team performed select representative sampling of states to serve as the proxy for assessing the practice of used electronics management across the U.S. They then assembled available information about the generation, recycling, export, recovery, reuse, and downstream flow of used electronics and developed a flow model, identified data gaps, and devised methods to estimate, or ascertain, unavailable data. They also assessed environmental and economic impacts of e-stewardship programs in the selected states.

They developed the e-waste flow model utilizing data pertaining to the sales, use (lifespan), de-manufacturing, and recovery (disposition) of electronic products. The goals for the material flow model included the following:

- Provide to state policy makers a decision-making tool with which to conduct scenario assessments
- Estimate the future quantities of used electronics for which appropriate infrastructure is needed
- Estimate the flow of specific quantities of e-waste materials (e.g., CRT glass in storage, recycled, or exported)
- Identify data gaps for trade flows of used and scrap electronics, flows invisible to trade statistics
- Compare the practices of different states

Dr. Glaser stated that the model required significant data including time period, region (city, state, country), type of consumer (commercial, institutional, residential), product sales, product weights (average or model-specific weights), product life spans (including reuse), and EoL management pathways (reuse, recycling, disposal, export). However, he identified several data gaps/limitations such as limited regionally distinct data on sales, collection, and disposition; lack of product sales projections; and limited characterization of regional flows and final disposition. Further, he noted that the ADEPT tool does not consider recycler market economics, e.g., impact of commodity market prices on recycling flow process.

Alberta Carpenter, Researcher, Environmental Engineering, National Renewable Energy Laboratory

Dr. Carpenter discussed tools developed at NREL to support a CE. She reinforced that a CE is a sustainability strategy that needs to consider unintended consequences and environmental impacts. She further referenced a definition of a CE as operating at multiple levels – “at the micro level of products, companies, and consumers, the meso level of eco-industrial parks (EIPs) and similar networks; and the macro level of city, region, nation, and beyond.” Such a scope requires thinking outside of industry silos.

Dr. Carpenter explained factors that need to be considered to evaluate a CE, which in the most simplistic sense include mass and time, i.e., accounting for material use (and loss) across life cycles. However, this approach can miss significant environmental and social impacts. Dr. Carpenter explained five comprehensive factors to evaluate a CE:

- Material use and efficiency: how much material is necessary to manufacture a product or operate a system and is the design and production process efficient and provide a valuable, necessary function to society?
- Temporal: What are product lifespans, use intensity, ability to be repaired or refurbished, and how are evolution of products evaluated?
- Spatial and cross-sectoral: Where is material being used and recovered, and where are losses in the system? What are the industries, sectors, and processes in place to manage and perform recovery and ensure material is continuing to provide functional value to society?
- Sustainability: what are the environmental, social, and economic impacts across all life cycle stages, lifetimes, and sectors of the economy and geographies and how does it interact/impact media in the environment?

- Behavior: how do we model what both or the market and the consumer are doing and how can they make a difference in what is successful or not?

Dr. Carpenter discussed a methodology review performed at NREL aimed at understanding methods currently in existence to evaluate a CE. They compiled a series of methodologies, including LCA, material flow analysis and energy/exergy, environmentally extended input-output analysis, system dynamics, discrete event simulation, and agent-based modeling and evaluated strengths and weaknesses as well as relevance to a CE transition. They further mapped the methodologies based on different characteristics such as type of analysis (qualitative/quantitative), efficiency potential (technical, economic, market), temporal resolution (static or dynamic – hours to years), and scope (micro, meso, macro).

She spoke about research questions asked at NREL as they consider the future of energy technologies. The research questions fall under two categories: technology analysis and systems analysis. Within the former they ask whether the research they are doing is making a difference, and does it help or hinder a CE. Does the technology have unintended environmental consequences? Is the technology economically feasible? In systems analysis they ask what are the regulatory barriers? How does the technology work within the existing (and maybe future) economic and industrial system? What are the decision factors for the different actors in the system? Where are the bottlenecks in the larger system to include producers, consumers, material recovery/repair/remanufacturing actors? Dr. Carpenter then explained several projects at NREL including dynamic material flow analysis methodology for PV systems, agent-based simulations of the CE, development of a circular economy lifecycle assessment and visualization (CELAVI) framework, bio-optimized technologies for keeping thermoplastics out of the landfill and environment (BOTTLE) analysis approach, and the Federal Data Commons life cycle analysis research and data repository.

Carol Handwerker, Professor of Materials Engineering and Environmental and Ecological Engineering, Purdue University

Professor Handwerker began explaining her background as a developer of large-scale, mass produced technology with experience in technology transitions. As such, she has experience developing collaborations to transform communities and supply chains. She explained that while the context of her talk would be on circular hard disk drives (HDDs), her talk would not be technical in nature, but rather focus on the social interactions and dynamics of transitioning to a CE for HDDs. Specifically, she spoke about a framework developed by Elinor Ostrom, 2009 Nobel Prize winner, focused on Sustainable Social-Ecological Systems.

Dr. Handwerker explained the project performed with the International Electronics Manufacturing Initiative (iNEMI) as a collaboration with organizations such as Google, Microsoft, Cisco, Seagate, national labs, and others, aimed at demonstrating a CE for HDDs. They employed Ostrom's framework for self-managing, sustainable, self-assembling systems to develop an explicit plan and identify the system, stakeholder, and data requirements for the project. They identified what types of organizations were needed for the project and recruited members of each category to participate. They then collaboratively evaluated existing value recovery options from HDDs and identified additional pathways. These included pathways such as reuse of HDDs, recovery of key HDD components for reuse and remanufacturing, and REE recovery from HDD magnets. The team specifically identified more than five paths for high-volume, economically viable REE recovery and successfully completed demonstration projects for each. In conclusion, Dr. Handwerker recommended the Ostrom Framework as a way to examine systems and the people in them.

Melissa Bilec, Associate Professor, Civil and Environmental Engineering, University of Pittsburg

Professor Bilec spoke about the intricate links between the high-tech world and the built environment. She stated that annually, embodied carbon (i.e., the carbon footprint of a material, including the amount of GHGs released throughout the supply chain) is responsible for 11 % of global greenhouse gas emissions and 28 % of global building sector emissions. New construction projections to the year 2050 estimate that embodied carbon emissions and operational carbon emissions will be roughly equivalent. Dr. Bilec also noted that the International Energy Agency (IEA) predicts high growth in renewable energy utilization in all sectors with the highest increases in the building sector (i.e., higher than the industrial or transportation sectors).

She provided four overarching messages, beginning with the need to develop baseline information. Such information might include the number and materials composition of buildings across regions, as well as projected changes to the building stock. Such information, which Dr. Bilec stated is woefully limited in the U.S., is necessary to perform urban mining.

Her second message focused on advancing assessment methods. She argued that LCA and material flow analysis (MFA) are key in this regard, but there are limitations to both. She identified several limitations to the application of LCA in a CE, including: the allocation between different building life cycles; limited guidance on consequential LCA for buildings; perfect substitution versus rebound effect; estimating durability and quality loss from reused materials; the invisibility in LCA of benefits of CE strategies like design for disassembly and reuse; LCA needs to move from a single life-cycle approach towards a multiple life-cycle approach to support continuous loops of products and materials; and the reuse of building components requires a trans-scalar sustainability performance method from material to urban scale. Dr. Bilec referred to PV products as an example, stating that while much focus is given to disassembly of different materials, we must consider how to assess that practice and account for different materials in LCA and MFA.

Dr. Bilec's third message involved on the need to transform design. She stated that achieving CE goals will require innovation that spans every scale of a product, from molecules to the built environment. Disassembly and reuse can occur at a molecular level from early-stage technology design and reuse and remanufacturing can be applied at a product or component level. Further, she claimed that each phase of a product's life cycle requires and interacts with urban and industrial infrastructure. In a truly circular system, the facilities and infrastructure needed to design, manufacture, sell, collect, disassemble, and recycle goods are also designed for circularity.

Her fourth message focused on understanding the role of people in a CE. She stated that there are still unanswered questions including what are the potential unintended societal consequences of CE strategies in the built environment? And how can CE in the built environment foster equity and social justice? She argued that we need to move beyond engineering and invite other disciplines to the conversation to converge around a CE. She provided a quote worth repeating by Foster (2020): "Implementing circularity is a fundamentally social process that will need to go beyond niche initiatives to social acceptance at the macro level."

Speaker Q&A

Questions of the speakers included the following:

- To what extent is waste considered a national security threat?

  Response (paraphrased): Dr. Handwerker responded that for products containing critical materials, there can be a security threat associated with those (e.g., neodymium, terbium, dysprosium, high purity graphite, cobalt). Critical materials can be tied up in mining waste. Lots of rare earth elements are lost/sequestered in radioactive mine tailings, for example. Dr. Glaser further added that one of the things the EPA faces with regards to strategic materials is the diminished use of critical elements; therefore, for a given mass of waste, recovery becomes more expensive.

- Directed to Dr. Glaser (EPA): do you have any tools that can be used to quantify the benefits of EV battery recycling? Specifically, in EV second life reuse?

  Response (paraphrased): Dr. Glaser responded that this is an active research area. And the EPA is looking at lithium-ion battery issues. One specific issue is that of LIB combustibility. Dr. Glaser spoke of a disposal site where a lot of batteries were just discarded, and when the EPA went in with superfund to clean up, they found that some items were so combustible they had to put them in special plastic bags to avoid contact. He noted instances of semi-trucks blowing up because of indiscriminate handling of li-ion batteries. Dr. Carpenter added that NREL has been doing a lot of work on evaluating how to recover and reuse batteries and battery components. She stated there are challenges with certifying it safe in second life applications. Further, as batteries evolve, the chemistries evolve also, and as a result, EoL challenges exist about whether and how they can be de-constructed for material or component extraction. She noted that the ReCell center (funded by DoE) is putting a lot of effort here. Dr. Glaser replied that he would like to see the larger LIBs recycled, especially into supporting grids. He asked whether any kind of standard definition exists of what is an acceptable condition for that battery? Can we distinguish between ones that are similarly good and will last for some time vs. those that won't last? Dr. Carpenter responded that that must be part of the testing procedures, or if extracted components could be used for stationary applications that could be applied (residential, grid, dispersed applications in e.g., e-bikes). Directed to Dr. Bilec: to her point of including people in a CE, how do we support the inclusion of users and owners?

  Response: Dr. Bilec identified strategies that can aid in this effort. One is increased stakeholder engagement during proposed technology development. She referenced a project involving engagement of farmers to identify agricultural products for use in the built environment. Another strategy is the use of community-based research approaches. Dr. Carpenter added that NREL has been using agent-based models to better understand the human behavior aspect for the different stakeholders, which is based on existing data. But where that data does not yet exist, you can use the engagement strategies Dr. Bilec mentioned. This is necessary to identify certain conditions in the community that drive behavior, to forecast behavior in response to incentives, or to understand consumers to gauge how successful a strategy may be.

- What can NIST do to help support these large-scale efforts? It sounds like databases are needed, but specifically what data and in what format are needed?

  Response (paraphrased): Dr. Glaser responded that one of the problems they ran into when developing the ADEPT tool was looking for databases. They considered using bills of lading, but discovered they are now considered business-sensitive information. They also considered data from the Census Bureau but found that the granularity they needed was not readily available. Therefore, they determined that sales data was really the only way to get the information needed. Dr. Handwerker recommended a follow-up workshop specifically about data and modeling needs. Dr. Bilec also noted that databases must cross sectors for innovation to happen between and across different sectors.

- Is design for recycling anathema to commercial acceptance? We must get acceptance on the part of consumers that perhaps clunkier, less consolidated devices are better. There is a tension between design for recycling and acceptance.

  Response (paraphrased): Dr. Handwerker responded that it is outdated to think that design for recycling produces clunky, boring stuff. Further, if we look at it as design for recycling, that's only one part. We're designing for sustainability. Dr. Carpenter added that evolution has to occur in material processing and recovery. Have to keep our mind open for that evolution. Dr. Glaser contended that designers are focused on performance and nothing else, they don't think about these ancillary items at all. Dr. Handwerker referenced Dell, who developed a casing for computers that is up-cycled., using wasted carbon fiber from aerospace. So, it can be done, but it is not being done very often. It takes vision, persistence, and commitment. Dr. Glaser gave another example of HP printer bodies, which use recycled material.

Session 4: Reuse, Repair, and Refurbishment in a Circular Economy

Kyle Weins, CEO, iFixit

Mr. Weins introduced his organization as one that provides a free repair manual for everything – their mission is to enable everyone to repair everything thing they own. He stated that the tighter that you are to the innermost circles of the CE, the more economic value you are going to create and capture. For instance, according to Mr. Weins, Apple pays Foxcon about $5 to assemble a phone, whereas one can have a battery replaced in a phone for $30-$40; 6-8 times the economic value. Repairable products make good sense: good for manufacturers, good for the economy, good for the environment, and good for the rest of us. Mr. Weins further called for a Repair Jobs Revolution, arguing that repair jobs may be an answer to the global unemployment problem, help bridge the digital divide, and cut down the amount of unnecessary waste.

iFixit produces a repairability index for products, rating on a scale of 1 to 10 how easy a product is to repair. Mr. Weins stated that on January 1, 2021 France became the first country to enact a national repairability scoring system where products are labeled based on a similar rating system. He provided several examples, with explanations, of scores iFixit gives to different products.

Mr. Weins provided several recommendations to support design for repair, including:

- Use modular assemblies that enable the replacement of discrete components
- Ensure easy access to parts likely to need maintenance. Use self-locating parts.
- Label and color-code parts to enable troubleshooting.
- Standardize between product lines and across generations.
- Make technical documentation freely available or open-sourced.
- Include parts list and part numbers.
- Create user interfaces and troubleshooting tools to diagnose problems.

He also discussed Right to Repair, a movement and associated legislation that is intended to allow consumers, or any service provider they chose, the ability to repair or modify their equipment. Currently, OEMs require consumers to use only their offered services or those of authorized vendors. Mr. Weins explained that Right to Repair necessitates the availability of parts, tools, and information, and so far in 2021, 20 states introduced legislation with the intent to make such resources available. According to Mr. Weins, the key to enabling a repair economy is products that are repairable and people with access to the information to be able to fix things. His organization, iFixit, is trying to support that by creating an open-source repair economy.

Eric Lundgren, CEO, Big Battery

Mr. Lundgren explained the history of his company which he says is the only second life battery processor that is repurposing and reusing EV batteries at scale in the U.S. His business is growing exponentially, expanding into new 100,000 sq-ft facilities every six months. In 2020, his company re-purposed 427+ megawatt hours of batteries, providing solutions for 30,000 batteries, and sent over 19 million pounds of EoL batteries that tested negative to a certified commodity recycler.

Mr. Lundgren discussed projections of the EV battery market, explaining that by 2030, 245 million EVs will be on the road. He argued that these batteries must be standardized, because the different form factors and chemistries make repurposing and recycling challenging. He further called for support for cell repurposing and the continued creation of profitable second-life solutions.

His business operations include collecting EV batteries no longer usable in vehicles, extracting the cells from the battery pack (recycling all proprietary components for commodity value), cycle testing, grading, and rebranding the cells as a BigBattery product and then repurposing them into new products to serve second- and third-life applications. Mr. Lundgren identified de-manufactured commodities to include steel or plastic housing, copper cables, printed circuit board components, copper bus bars, aluminum plates, aluminum connectors, plastics, and aluminum coolant systems. But the greatest value comes from battery reuse. Mr. Lundgren described Big Battery's products, which include repurposed single batteries, power packs, power walls, and portable power units that can be used in energy storage solutions, home power solutions, portable power applications, and lead-acid conversions.

Adam Shine, VP, Sunnking

Mr. Shine explained that Sunnking promotes responsible reuse, repair, and recycling of unwanted electronic equipment, specializing in e-scrap removal and ITAD (IT Asset Disposition) services for Western and Central New York companies. He provided a statistic from a 2017 United Nations University study that Americans throw away $55 billion in e-waste material annually. This is in part due to the consumer upgrade cycle where Americans upgrade computers every six years, tablets every 3 years, and smartphones every two years. However, Mr. Shine also noted that Americans often refrain from recycling equipment due to data privacy concerns, and thus value is lost in stored equipment. He argued that public education is necessary regarding proper data wiping/erasure, as well as where to take unwanted electronic equipment for reuse or recycling.

Mr. Shine discussed the need for a CE for electronic products, stating that 1 million recycled computers equate to five football fields worth of landfill reduction. CE benefits include the reduced need for mining of new metals, few carbon emissions, and less water consumed by reduced manufacturing. He explained that Sunnking tests and, if necessary, upgrades equipment to be sold for reuse. If whole equipment cannot be reused or refurbished, Sunnking extracts components for resale. Most equipment or components are sold online, through wholesale, or in retail stores. Products and components that do not have a resale value are recycled. He stated that on average, revenue from recycling across all product streams is approximately $0.12 per pound, whereas the value of resale is $2.51 per pound on average. So, there is significantly more value in reuse of electronics than recycling.

Mr. Shine talked about the impacts of the Covid-19 pandemic on the industry, stating that the resale market, particularly for refurbished laptops, increased as people transitioned to remote work. According to a 2020 Gartner, Inc. study, more than 80 % of companies plan to permit employees to work remotely part-time going forward, which may result in the continued utilization of refurbished devices.

Mr. Shine also discussed consumer rights to reuse/repair, explaining that while the benefits may be obvious, manufacturers have different wants and needs and therefore provide limited access to parts and manuals and restrict parts harvesting. This challenges Sunnking's operations and Mr. Shine argues that he believes it is critically important that people who want the ability to repair their devices are able to do so.

Nabil Nasr, CEO, The Remade Institute

Dr. Nasr discussed the immense potential that a CE can have on the economy as well as the environment. He provided several EU-based examples such as the CE's potential to grow resource productivity by up to 3 % annually in Europe, bring economic benefits of 0.6 trillion euros per year by 2030, reduce EU emissions from materials by 56 %, and reduce decarbonization costs of heavy industry significantly [26].

He then introduced The Remade Institute (Remade), which is a public/private partnership developing transformational technologies to accelerate the transition to a CE for plastics, metals, fibers, and e-waste. He explained that Remade is the first national initiative focused on the CE. Remade's mission is to reduce embodied energy and carbon emissions through early stage applied research and development and accelerating the transition to a CE. Remade's strategic goals includes developing transformational technologies that enable U.S. manufacturers to do the following: expand recycling, recovery, remanufacturing, and reuse; reduce primary materials consumption, increase utilization of secondary materials; lower energy consumption and emissions; and achieve cost and energy parity between primary and secondary materials.

Dr. Nasr provided context behind the development of Remade, explaining the environmental challenges resulting from global scrap market disruptions, poor U.S. plastics recycling rates, and plastic waste contamination in oceans. He stated there are significant challenges related to the volume of material ending up in the waste stream or in processes that are not capable of recovering the material back into the system. He pointed out the U.S. plastic recycling rate, which in 2015 was estimated to be 9.1 %, but is estimated to have decreased to 4.4 % and 2.9 % in 2018 and 2019, respectively. This recycling rate is far behind other countries, and, in fact, behind the global average. Dr. Nasr noted the value of plastic landfilled each year in the U.S. to be approximately $50 billion. The realization of these factors led to the establishment of Remade.

Dr. Nasr explained that solving these issues requires a comprehensive systems level approach guided by national goals and metrics and that address industry needs and priorities with a path to implementation and commercialization. Remade efforts are therefore focused on systems analysis and integration, design for reuse, manufacturing materials optimization, remanufacturing/EoL reuse, and recycling and recovery. Dr. Nasr presented the diverse membership of Remade which include industry, academic, affiliate, and national laboratories. He then identified a selection of remanufacturing, recycling, and recovery projects currently underway.

Josh Lepawsky, Professor, Department of Geography, Memorial University

Professor Lepawsky described several fundamental limits to a CE, beginning with the Jevons Paradox: the idea that as efficiency increases, overall demand for energy and materials also tends to increase. This is also referred to as a 'Rebound Effect', the trap of per unit efficiency. A 'circular' but growing economy means energy and materials must continue to be added: i.e., no economy or company can reduce total throughput of energy and materials and still grow. In this sense, material complexity works against reuse and recycling, for example the growing use of alloys which are exceptionally functional, but not recyclable. Further, energy cannot be recycled, e.g., the waste heat from one computer cannot be used to power another computer.

Dr. Lepawsky compared the amounts of waste generated during the mining, manufacturing, and post-consumer stages of electronics lifecycles; stating that waste from mining operations far exceed those from other lifecycle stages and therefore CE efforts need to be aligned with the problem. He argued that repair of consumer devices will reduce the amount of post-consumer e-waste generated but will become increasingly disconnected from and poorly suited to the scale of waste arising from resource extraction for and manufacturing of electronics.

He discussed the CE challenge resulting from the complex arrangement of industrial systems. The locations of supply networks and infrastructure does not necessarily align with those of reuse, repair, and refurbishment practitioners. Further, Dr. Lepawsky explained that sectors such as automotive, electronics, etc., are no longer distinct from one another.

Dr. Lepawsky talked about Standard EN 45554 “General methods for the assessment of the ability to repair, reuse, and upgrade energy-related products” published by the European Committee for Electrotechnical Standardization (CENELEC). This is the legally mandated standard Mr. Weins referred to that aims to quantify the repairability and reusability of products developed in the EU and brought into force in France in January 2021.

Presenting several maps displaying the geographic distribution of the electronics maintenance and repair industry, Dr. Lepawsky highlighted the widespread activity throughout Europe, the U.S., Africa, and SE Asia, i.e., developed as well as developing countries. Last, he discussed the environmental offsets of electronics repair, noting that extending device life by one year can reduce the consumption of new units by 15 million units and reduces carbon emissions that would otherwise result from manufacturing new units by 3 million tonnes of CO_{2eq}. Extending device life by four years reduces consumption of 50 million new units, saving 10 million tonnes of CO_{2eq}.

Speaker Q&A

Questions of the speakers included the following:

- Recycling of computers and phones – research at intel shows that consumers have an emotional attachment to devices, these are big factors related to recycling inertia. How can we overcome that?

  Response (paraphrased): Mr. Shine responded that when recycling electronics consumers want to make sure they use a certified vendor (R2 or e-stewards certified). Consumers should work with them to make sure they handle the data appropriately. He also recommended data storage on the Cloud instead of storing data on devices.

- Will Big Battery take nickel cadmium batteries?

  Response (paraphrased): Mr. Lundgren stated that Big Battery does not take nickel cadmium batteries; rather they only take the newer technologies (e.g., lithium ion, NMC) because those batteries have the longest life cycle that is being prematurely demised. These represent the largest volume currently being replaced

- What happens to your batteries at Big Battery? That Big Battery sells?

  Response (paraphrased): Mr. Lundgren explained that the batteries get used for hopefully 10 years in a new application. When that application is over, Big Battery offers a free reverse logistics program to direct them to an R2 certified recycler for commodity processing. Big Battery pays the logistics for that.

- Can you talk to the need for standards to enable the repair/reuse of the CE? Recycling option? What standards would make it easier or better to push the reject material back into the economy?

  Response (paraphrased): Mr. Lundgren discussed that the UL certification standards are not set correctly for the repurposing of batteries. They're set for the mass production of a new battery but not the repurposing of all the batteries that are needing to be repurposed today, so he would like to see a new UL standard or a standard that would suffice to replace UL for specifically the batteries that they install in California and New York.

- To Big Battery: Do you see a role or have you already established a role for disassembly including robotic disassembly for reuse. And what are your criteria for everybody winning?

  Response (paraphrased): Mr. Lundgren explained that they already have robotic arms doing assembly. They also have laser machines in three facilities that are doing all the laser soldering work for battery management systems and thermal management systems. But they have to de-manufacture by hand. Their facility in Chatsworth, CA employs 131 warehouse employees that are demanufacturing all day long. Mr. Shine also responded, saying that there is no replacement for manual disassembly, especially if you're looking for value in parts or the units themselves. They must be assessed by somebody and then tested by somebody. He further explained a two-fold issue of recycling: nearly every unit now has a battery. Sunnking has started to shred lower grade consumer electronics that don't have resale value any longer. So rather than have somebody take apart a DVD player you must put it through a shredder. In the case of DVD player, it’s no big deal, but if it’s a Bluetooth speaker that either does not work or does not have value left in it, you must get the battery out before you can shred it. This is challenging given smaller form factors of units together with the fact that they are glued together, and not only glued together, but the components inside are glued down for shock resistance and impact. Mr. Shine explained that he met with several manufacturers at the Consumer Electronics Show (CES) a couple of years ago, and asked manufacturers why devices are becoming less recyclable instead of more and he got the response that manufacturers are aiming to produce products that sell to consumers. Currently, consumers want durable electronics (e.g., to continue functioning even if dropped), so, until consumers demand more sustainability in their products, that will not be prioritized.

- What policy changes are needed to promote reuse repair? Your businesses have worked in the current policy context, but how can it be made to scale to the level that we need to deal with going forward?

  Response (paraphrased): Mr. Weins stated the need to get some kind of equity around availability of information and parts to recyclers and refurbishers. It’s not going to work to continue the status quo where manufacturers pitch products out and then expect companies like Sunnking to figure out and reverse engineer how these products work. Reuse necessitates information on how everything works. Currently we have fragmentation: there’s over 5000 different Android handsets on the market. How are they constructed? Which parts are compatible between them? If we have other information, it dramatically increases the efficiency. He calls for legislation to level the playing field so that one large manufacturer doesn’t spoil it for everyone. Mr. Lundgren added that he would like to see adoption of recycling transparency. Would like to see the OEMs sharing what’s happening with their batteries, showing the closed loop solutions. Would like to see consumers pushing these issues.

Session 5: Best Practices for a Circular Economy

Adina Renee Adler, VP of Advocacy, Institute of Scrap Recycling Industries (ISRI)

Ms. Adler introduced ISRI as "the voice of the recycling industry promoting safe, economically sustainable and environmentally responsible recycling through networking, advocacy, and education." ISRI has more than 1,400 members which includes metals, paper, plastics, tire and rubber, textiles, electronics, and glass recyclers operating in 41 countries. Ms. Adler advocated that recycled commodities are valued for cost, energy, and environmental savings in place of virgin materials and meet 40 % of the world's industrial manufacturing needs. According to Ms. Adler, a CE is reliant on successful recycling, and the three main components of such recycling include lowering contamination, enhancing efficiency to lower costs of recycling, and improving market demand, whether locally or abroad. She expanded on the last point, arguing that recycled commodities are pulled entirely by demand, and thus trade is vital when local demand does not meet local supply.

Ms. Adler discussed the shared responsibility of government and the private sector in facilitating a CE, calling for the need to work synergistically to create balance between government intent and industry ability. She advocated for government oversight and regulation that is transparent, achievable, relevant, data-driven, notified, consulted, and clear. Industry compliance will then follow export/import regulations, business operations, and quality, environmental, and health and safety rules. She further argued for regulation that is enforced, where officials are informed, trained, empowered, and directed to act, and where industry compliance is supported by the removal of incentives to disobey, cheat, or otherwise violate the law.

Joanne Larson, Sr. Engineering Manager, Seagate Technology

Ms. Larson spoke about key challenges to HDD circularity, stating that HDD circularity can only be advanced through strong partnerships and development of engineering and financial data. She provided some background on levels of circularity for HDDs, speaking first to drive-level circularity which is focused on extending the lifetime by refurbish, repair, and re-deploy practices. She identified three challenges to drive-level circularity including 1) data security, concerns around secure data destruction by data erase protocols, 2) warranty, design for five-year lifetime for mechanical components (spin motor, actuator) and head-disc integration (tribology), and 3) design, MR technology and data storage demand have historically evolved extremely rapidly. Component and material-level circularity is focused on HDD recovery at EoL.

Ms. Larson discussed several circularity factors unique to HDDs. Unlike other consumer electronics and energy technologies, HDDs are mass-manufactured through processes that are exceptionally lean. HDDs contain an astonishing amount of technology, but the bill of materials is very inexpensive. Further, while HDD components are relatively small in mass, they are produced in the millions and distributed globally. Additionally, HDDs are one part of the supply chain: i.e., Seagate is a supplier in other companies' supply chains and therefore they have little to no connection with the user/owner of their product. A key technical barrier to HDD circularity is the component cleanliness requirements, in which HDD assembly and disassembly must be performed in a cleanroom. As a result, the infrastructure for component and/or materials recovery is capital intensive.

Ms. Larson noted that HDD circularity requires an extraordinary commitment between customers and HDD manufacturers. She explained that while some aspects of sustainability can be 'contracted out' to third parties/contractors, such as strategies for energy/water conservation and environmental compliance, that is not possible for HDD component/materials circularity (e.g., refurbishment). A partnership is necessary between HDD owners and manufacturers, which is protected by unique non-disclosure agreements (NDAs).

Ms. Larson discuss three laws of thermodynamics of HDD circularity:

> 1st Law: Materials are neither created nor destroyed, REE's and precious metals are less naturally abundant. And money is always involved (you can't get something for nothing).
>
> 2nd Law – You won't break even. Unlike biological systems, materials are not self-regenerating (mining cannot be made sustainable in ways similar to 'sustainable' fishing or forestry).
>
> 3rd Law – It's all downhill. S = k log W, S only increases; HDD manufacture and use case realities have distributed REE's and precious metals in certain patterns but also randomly, across the globe.

She also discussed opportunities and wishes for HDD circularity. These included legislation on e-waste versus circular components; movement trans-boundary; conditions for reuse; standardized definitions, including the need for language/descriptors in the continuum between 'prime/new' and 'waste'; customer paradigm shift from reactive/delegatory to innovation and ownership of solutions for circularity; incentives for HDD customers, similar to EPEAT points; increased prominence of LCA; and advanced recycling practices for REE and precious metal recovery and electrical component recovery.

Kathleen Fiehrer, Materials Engineer, Intel

Ms. Fiehrer discussed Intel's influence on chemical waste markets and alignment to the company's corporate 2020 environmental goals. She described Intel's efforts to improve the sustainability of the fab chemical waste produced in four semiconductor manufacturing facilities. In 2012, Intel produced 47,000 tons of fab chemical waste globally, and main management methods included incineration, recycling, and conversion to fuel blend. Ms. Fiehrer explained that fuel blend conversion is the use of waste solvent as an alternative fuel source to oil products and is a form of recycling that counts toward Intel's recycling indicators, but not considered reuse or recovery. In 2012 Intel established 2020 Corporate Sustainability Goals which included waste management according to the hierarchy displayed in Figure A9.

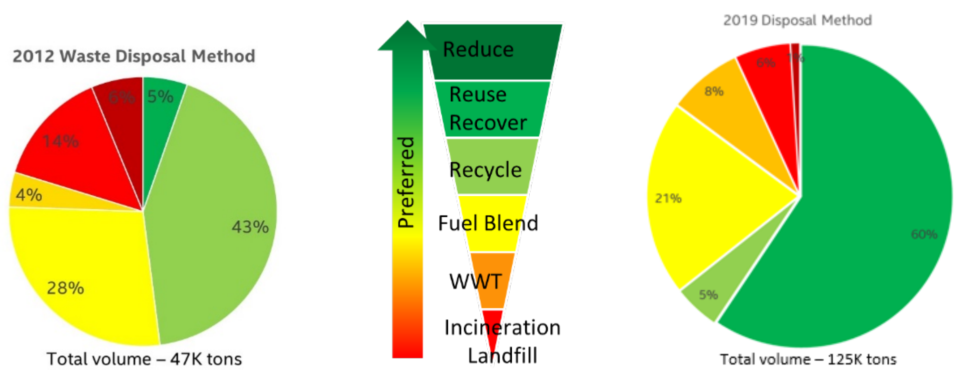


Figure A9: Intel's waste management hierarchy and waste disposal breakdown for 2012 and 2019

Although the total volume of waste increased between 2012 and 2019 (Figure A9), Intel significantly increased the percentage recovered for reuse, decreasing the amount sent to incinerators and landfills. This was realized through strategic partnerships with suppliers on disposal methods. Ms. Fiehrer spoke to the cost savings associated with this shift, stating that 49 % of disposal costs come from the actual disposal method (incinerations, fuel blend, etc.) while 45 % comes from the logistics associated with transporting the material from Intel to the disposal/processing site. She mentioned that shifting to closer disposal options, moving material in bulk, and transporting material via rail helped Intel achieve cost reductions. Ms. Fiehrer stated that Intel achieved their 2020 Waste Environmental Goals in 2019, including zero hazardous chemical waste to landfill and 90 % recycling of solid waste. They have since developed 2030 goals which include zero total waste to landfill and to implement CE strategies for 60 % of manufacturing waste streams.

She also provided opportunities for NIST which included developing incentives for suppliers engaged in circular economy recovery, including national local infrastructure, as well as development of water separation technology without heat or high pressure.

Mark Buckley, Founder, One Boat Collaborative

Mr. Buckley discussed the role of business in a CE and provided several examples of businesses practicing circularity. He asked the big question of how do we create the greatest economic/business value with the lowest overall environmental and social burden on the system as a whole? He quoted the World Economic Forum and Ellen MacArthur Foundation claiming we can see an "anticipated $4.5 trillion in annual economic benefit from the CE while halving the environmental footprint associated with resource development and production."

He indicated that what got us here cannot create the change that we need, referring to the need to shift to a circular rather than linear economic model. He discussed several key features of circular versus linear systems; beginning with the concept of biomimicry and the need to learn from natural systems. He also stated that communities are critical as no one organism survives and thrives by itself in an ecosystem. In addition, interdependence and understanding externalities are critical. He also noted that in a CE, systems are dynamic not static, as change is the only constant. And he mentioned the need to foster uncommon collaboratives, especially with sectors that have not been engaged in the past.

Mr. Buckley spoke about several CE pioneers including Nike, Davies Office, Patagonia, Eileen Fisher, Xerox, among others and explained circular practices employed. He discussed companies performing service versus asset ownership, such as Zipcar, Airbnb, Philips Lighting, Rent the Runway, etc. He also talked about the role of companies in decarbonizing the economy which can be performed through committing to carbon reduction goals and collaborations with supply/value chains to meet those reductions.

Mr. Buckley discussed the role of design in a CE, arguing for the incorporation of sustainable/regenerative criteria into all design. Businesses can create demand to reuse recovered materials at their highest economic and utilitarian value as well as can create new and robust demand for recovered and recycled materials. Companies can take guidance from certification programs such as EPEAT, Living Building Challenge, LEED, Cradle to Cradle, etc.

He also noted the important role of procurement in a CE, stating that businesses can develop common language supporting circularity and *convey intent* in RFIs (requests for information) and RFPs (requests for proposals) to signal demand and need for innovation. Businesses need to build in EoL requirements for reuse, remanufacturing and recycling and leverage supply chains and spheres of influence in shaping and building robust secondary materials markets.

Mr. Buckley offered six keys to business accelerating the transition to and creating a CE:

- Build the circular economy "eco system"
- Create uncommon cross-sectoral collaboration
- Understand the role of life cycle design for all products and materials
- Diversion and recovery of material does not constitute success
- Robust, resilient, and cost competitive markets for remanufactured cores and secondary feedstock must exist to attract infrastructure development to collect and return these materials

- Well-constructed national and international policies. Business must be a partner and help craft thoughtful effective policy and regulation and leverage sector leadership and dismiss sector laggards

Corey Dehmey, Executive Director, Sustainable Electronics Recycling International

Mr. Dehmey discussed the role of standards and certification programs in a CE. He stated that "living in a CE world requires making sustainable decisions with our used electronics, every time." This extends beyond deciding what should be done and also considers how it should be done and choosing who is going to do it right. Mr. Dehmey explained that while sometimes making the right decision is easy, e.g., when social pressures are present, there is a desire to protect privacy/intellectual property/data, and there are positive market dynamics, other times the choice is much harder (e.g., ignorance, negative market pressures, cost). So, in a world with such complex decisions and competing forces, it is necessary to have best practices in place to decide the appropriate option. Mr. Dehmey explained that this is the role of standards: to identify and document best practices to meet the goal and achieve a CE. Certification then creates accountability to the best practices. Mr. Dehmey stated that standards are important to make sure products and materials are handled the same way regardless of their value.

Mr. Dehmey explained the R2 standard as a case study, which requires a hierarchy of reuse first followed by materials recovery second. As such, R2 covers the realms of returns, repairs, trade-ins, upgrades, remarketing, and recycling. In a CE model, every scrap of functionality has been used by the time a product goes for recycling. At that point it must be managed properly to be able to recover the materials, and this is where we must require recycling.

Speaker Q&A

Questions of the speakers included the following:

- Directed to Ms. Fiehrer and Ms. Larson: Is there discussion within your companies of how to expand the responsibility for product reduction recycling of your products after it reaches the consumers?

  Response (paraphrased): Ms. Fiehrer stated that at the end of the day we are a motherboard or a component manufacturer. We want to work with our customers, but a lot of the end-of-life opportunities are with our customers and the large OEMs. But we are certainly engaging with them on how we can improve the life cycle and the life management. Ms. Larson responded that Seagate products go to businesses, primarily. Seagate is involved in discussions with customers. End consumers are a minor part of where the drives reach end of life.

- Has the EPEAT standard which now gives extra points for disk drives containing 5 % or more recycled magnet content, made a difference at Seagate and its customers?

  Response (paraphrased): Ms. Larson responded no, from the point of view that Seagate cannot report recycled content for those magnets. We can tell you the mass of the magnet, but we cannot tell you the percent of recycled content, such neodymium, or the magnet material. People speculate that there is actually 5 % recycled content in those magnets but certifying or documenting it is a whole different conversation.

- Are there ways to develop and promote data sanitation standards? So, people don't feel the need to destroy hard drives.

  Response (paraphrased): Ms. Larson stated that yes, NIST has a standard for data erasure. Seagate does offer the software to destroy/erase data. Mr. Dehmey also responded that destroying HDDs for the sake of data erasure forces the production of new HDDs. He argues that instead we need to change the dynamic so that we all have the security that the data is gone, but can still extend the life of the HDD.

Session 6: Breakout Discussion

Slido was used to solicit responses to questions on the topics of Enabling a CE, Design, Use/Reuse, and EoL Management. Questions were formatted as word clouds, multiple choice, and 'ideas' where participants could provide a text response and up vote/down vote responses. Following the Slido questioning, open discussion was facilitated on outstanding topics. Key takeaways from the session beginning with Slido questions/responses are as follows:

Enabling a CE

- What the appropriate metrics for a circular economy?

  The top five responses (based on participant upvoting) included: decreasing purchasing of virgin products, modular and replaceable; % recycling; consumer behavior; and reduction in footprint; measured by GHG emissions and toxics.

- What are the needs for talent acquisition in the circular economy?

  The top five responses included: multidisciplinary understanding; economists and behavior science experts; industrial ecologists and material scientists; transdisciplinary skills; and human factors engineers.

- What types of standards and certifications would help facilitate circularity of solar panels, batteries, and electronic products?

  The top five responses included: trust in waste management; electronics - standardized reporting on materials in and materials out from recyclers; standard for communicating material content, repair, refurb, and recycling instructions; battery standards for second life; and state of batteries.

- What are data challenges and needs specific to the circularity of solar panels, batteries, and electronic products?

  The top five responses included: data on materials used in various products - either at the product level or component level; what is a battery's state of health needed for different applications; quantification of what materials are in each product and predictions for how this will evolve over time (solar panel 40 years ago is very different than one produced today); consistent battery state of health measurements; and easily found data describing product composition (BoM and materials) and product description enabling disassembly.

- How can tools such as life-cycle analysis and techno-economic analysis be enhanced or adjusted to better facilitate a circular economy?

  The top five responses included: Expand scope to include multiple product lives; actual materials composition; focus groups about why they trash stuff (fire damage, hurricane, luxury); transparency of current use in industry and governments; and integrate explicitly into all engineering programs around material and product design and manufacturing.

Design

- What challenges exist to designing for end of life?

  The top five responses included: materials science; cost; education of designers; integration into product design tools; and manufacturers need to collaborate.

- What challenges exist to using earth abundant versus rare materials?

  The top five responses included: performance equivalence; proper disposal and usage; materials science; rare materials have many properties that earth abundant don't; and technology advancement requirements.

- What is needed to increase the use of earth-abundant materials versus rely on rare materials?

  The top five responses included: performance; R&D to show feasibility; incentives; investment in materials science for performance; and integrating sustainability early in tech development.

- What challenges exist to using recycled versus virgin materials?

  The top five responses included: purity; collection and sorting; real cost not reflected; performance; and may be cost prohibitive.

- What solutions could help to overcome challenges to using recycled materials?

  The top five responses included: design standards; infrastructure of recycling facilities & transportation; for batteries and electronics; better ease of removal of parts; better processes; and standards around what must be reused.

- Is design for circularity in conflict with a capitalistic economy? (multiple choice question, percentage represents respondent breakdown):

  Yes: 25 %
  No: 75 %

- How can NIST facilitate design for a circular economy?

  The top five responses included: standards for manufacturers, developed with industry; promote standardization; help harmonize data and study findings; creating a list of materials and processes recommended for change; and develop sophisticated databases from the myriad that already exist.

- Are there other design challenges or needs that have not yet been discussed?

  The top five responses included: Integration into product design; reversible fasteners; rapid material composition fingerprinting; How can IP be protected in a field where we want publicity; and alternative to adhesives but maintain thin.

Use/Reuse

- What are challenges to ensuring the security of data on electronic devices during reuse?

  The top five responses included: removable storage media; standard practices for data wiping; customer confidence and understanding the process; standard centers; and centralized/trusted centers that will follow data wipe standards (not local PC repair shop).

- What challenges inhibit extending the life of products whether through repair, remanufacturing, or refurbishing?

  The top five responses included: embedded batteries; lack of motivation from manufacturers; disassembly; sexy new products; and lack of emotional attachment.

- What types of standards and certifications could help extend use/reuse?

  The top five responses included: assembly/disassembly standards; performance standards; standards that support easily swappable batteries; best practices for disassembly; and standards for assessing state of spent batteries.

- How can talent acquisition in the use/reuse industry be supported?

  The top five responses included: education on reusable culture; co-op education training; national apprenticeship programs; cheap labor – do in prisons or get high school students to do the work; and value reuse as much as new product design.

- How can secondary markets for used/repaired/refurbished products be expanded?

  The top five responses included: warranties; right to repair laws; significantly higher price for virgin goods (luxury tax); reduce risk; and performance standards and certifications.

- What are other challenges and needs for extending the use/reuse of solar panels, batteries, and electronic products in the circular economy?

  The top five responses included: no consistent signal for producer responsibility; fractured regulatory/solid waste framework in U.S.; access to collection; incentives for recycling; and standards for repair and certification standards for afterwards.

EoL management

- Should AI and robotics be employed in the EOL management of: (multiple choice question, percentage represents respondent breakdown)

  Solar Panels: 0 %
  Batteries: 6 %
  Electronics: 6 %
  All of the above: 89 %
  None of the above: 0 %

- What challenges exist to the application of AI and robotics to facilitate a circular economy?

  The top five responses included: cost; huge variations in the input products; model training; supply; and scale.

- Which entity/group should have roles in accountability for End-of-Life management? (multiple choice question, percentage represents respondent breakdown)

  Manufacturer: 29 %
  Owner: 5 %
  Regulatory entities: 0 %
  All of the above: 67 %

- What challenges inhibit the effective collection of devices for proper EOL management?

  The top five responses included: no infrastructure; lack of incentives; fires; lack of access to collection sites; and convenience.

- What challenges impede the sorting and disassembly of devices? If speaking specifically about a product type, please identify.

  The top five responses included: embedded batteries; complexity of structure – proprietary build; disassembly is not taken into account as part of the design; no standard labeling of batteries; and material ID and composition.

- What are solutions or needs to overcome these challenges?

  The top five responses included: design for disassembly; material labeling; optical sorting using QR codes; infrastructure (network) of disassembly facilities and local training; and Best Practice Guides that support "Right to Repair' rules from other agencies or disassembly requirements.

- What are other challenges or needs for effective end-of-life management of solar panels, batteries, and/or electronic products?

  The top five responses included: toxic material; how to keep supply chain consistent; OEM interest; the overlap between metals and polymers recycling/end of life; and materials marketplace.

Open Discussion Topics

- Blockchain as distributed ledger for tracing material content
  Participants stated that a lot of effort is going on in this space. Blockchain could be utilized for traceability for authenticity of repair parts, the history of product/component use and repair and so on, similar to a Carfax report for cars. It is the data in what's called a distributed ledger that's created as part of the block chain. Because it is spread out and there is no one owner, it cannot be manipulated. It's a way of reducing fraud. Applications could include tracing a material or material composition; could be about tracing assets. About avoiding fraud, counterfeits. Prevents falsification of records. It also supports standard producer responsibility programs – avoid issues of double counting of the weight recycled. A lot of it is being looked at from new manufacturing, once a new device goes on the market, having traceability throughout the lifecycle of that device. A group called Obata is working on the topic.

- Lithium-ion battery fires

  Participants discussed the challenges posed by the ignitability of LIBs. They stated that batteries, in general, are a real challenge to reuse and recycling. A participant from the EPA noted that the EPA has developed some approaches to dealing with discarded batteries that they have developed on the fly because of the temperamental nature in a discarded state. There is no easy way to distinguish one that is prone to blow or ignite. Their approach is to put LIBs into separate plastic bags to minimize the fire effects. Another participant recommended that NIST come up with circumstances to let people understand and know the conditions where you can trust the battery versus not trust the battery. What are the conditions? Are they easily observed? Do you need other detectors to determine the circumstances? Someone else suggested getting Sandia National Laboratory involved in that. Sandia has done a lot of work with lithium-ion batteries and developing standards as well.

- Education of the public as well as recyclers

  Participants discussed the challenge faced by recyclers regarding lack of information about the safest and best methods for discharge and storage of batteries. There are a lot of hacks that people use (deep salt solutions and sand and such). There is a need to develop safe and reproducible standardized methods for discharge, safe handling, etc. Additionally, a participant stated that education of the public is huge. Nobody knows what to do with electronics: people wish-recycle and put it in recycle bin, which contaminates municipal recycling and has been a source of fires in material recycling facilities.

- Labeling

  Participants noted that products on the outside look virtually identical. One might have a lithium-ion battery while another does not. A recycler doesn't know what they are going to be processing until they invest the time and labor to open it. That effort may not even be needed. Labeling that provides information about whether a battery is even in the product is critical. Furthermore, labeling of the cathode chemistry can inform processing decisions. It appears that Big Battery and other companies have systems to address this challenge, other, particularly smaller processers may need that information to direct materials to the right pathways.

Appendix D. Slido Questions and Responses

Appendix C provides a compilation of the input and ideas raised by workshop participants during the event. The appendix is organized by session. For "idea" questions, experts were able to upvote, downvote, and comment on the responses of others. For those questions, the number of upvotes/downvotes received and total overall score (indicating participants' highest priorities) are shown in the tables below.

Day 1 Introduction

1) What is your role in the circular economy? (n=81)

Government – Federal: 28 %
Producer/Manufacturer: 14 %
Nonprofit: 12 %
National Laboratory: 11 %
Government – State: 9 %
Academic: 7 %
Industry Organization: 7 %
Recycler: 6 %
Other: 4 %
Reuse/Repair: 1 %

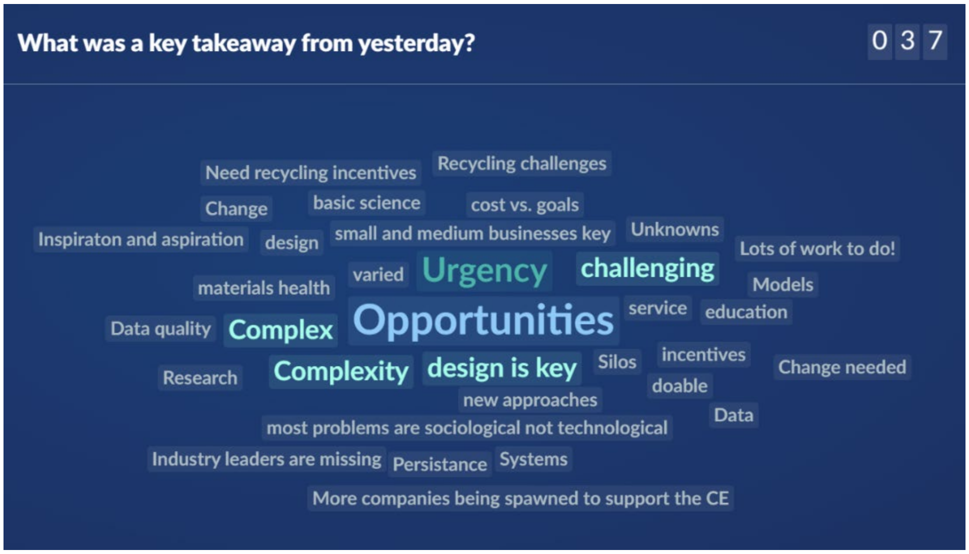
2) What is a major challenge to a circular economy for high-tech products? (n=76)

Day 2 Introduction

1) Were you familiar with NIST before this workshop? (n=48)

Yes: 81 %
No: 19 %

2) What was a key takeaway from yesterday?



3) In your part of the circular economy, what is your greatest data need?

Session 2A: Electronics Recycling Challenges

1) What is your role in electronics recycling? (n=33)

Researcher: 36 %
Government: 24 %
Producer/Manufacturer: 15 %
Recycler: 15 %
Industry Organization: 6 %
Other: 3 %
Reuse/Repair: 0 %

2) What does a bad day look like at a recycling facility?

Responses	Score	Upvotes	Downvotes
investment in infrastructure	1	1	0
National electronics recycling requirement and increased use of purchasing power to drive change	1	1	0
New legislation	1	1	0
EPR policy, to make products reflect true cost of disposal/EOL management. That is now hidden from consumers, and exported by manufacturers	1	1	0
Reaching out to the people who don't think like us.	-1	0	1
Align incentives	0	0	0
Accessibility	0	0	0
John was right. Education	-1	0	1
Reaching out to people not open to education.	0	0	0
consistent funding for collection infrastructure	0	0	0
Make electronic recycling easy for consumers and businesses	0	0	0
Marketplace for reuse of materials	0	0	0
Determining the barriers to acceptance, cooperation.	0	0	0
More communication across value chain	0	0	0
more consistency across state and local lines	0	0	0
Quit trying to do the same things and expecting different results.	0	0	0
consumer education	0	0	0

3) To what extent does lack of appropriate data impede your ability to be more circular? (1=not impeded by lack of data, five = very impeded by lack of data) (n=30)

1: 3 %
2: 7 %
3: 3 %
4: 33 %
5: 53 %

4) What specific data would you benefit from? (e.g., LCA data for products, recycling operations and processes, materials content of products, etc.)

Responses	Score	Upvotes	Downvotes
Material content	5	5	0
Standardization of components	3	3	0
transparency from manufacturers	3	3	0
Reuse market potential	3	3	0
material content of products	2	2	0
material content of products on a durable label	2	2	0
LCA data process variation material content upstream material manufacturing process data	2	2	0
Knowing who can receive our e-waste materials to do something with them; and where we can get recycled materials as source.	2	2	0
Materials SDS	1	1	0
Parts availability	1	1	0
Materials content	1	1	0
Material content	1	1	0
recycling operations and processes	1	1	0
data on management processes	1	1	0
Value of materials	1	1	0
LCA data to inform decision making	1	1	0
Advance notice & input for regulation change	0	1	1
material content and how/if segregated	1	1	0
presence and location of hazardous components	1	1	0
Value of components	1	1	0
material content	0	0	0
Easy access to harmful components	-1	0	1
LCA data - more! recycle options - more detail	0	0	0
material content	0	0	0
Info on impact of specific materials on recycling stream	0	0	0
Sustainability tradeoff information for specific materials to guide design choices (e.g. plastic vs. aluminum)	0	0	0
material content of products	0	0	0

5) What standards, either documentary or reference materials, would enhance recycling of electronics?

Responses	Score	Upvotes	Downvotes
R2v3	3	3	0
Standards need to be more specific about HOW activities will be completed. The guidelines are too broad.	2	2	0
recyclers downstream transparency	2	2	0
R2v3	1	1	0
EERA type standard that certifies that electronic materials are recycled properly in a sustainable way	1	1	0
standards for providing full material declaration on the product (via QR or bar code) so recyclers can know what they are managing	1	1	0
Simple way to store and share and capture device info: model, an, etc.	0	0	0
Material Content quality	0	0	0
Disassembly details	0	0	0
standardized definitions and then reporting of types of electronics received and commodities sent	0	0	0
eStewards	0	0	0
R2	0	0	0
NAID	0	0	0
Global documentation standards for materials and processes used	0	0	0
A good equipment to material recycling categorization	0	0	0
We have R2 and E stewards. Need better info on recycled content feasibility, recyclability of certain materials, ability to require extended warranties in standards, software upgrades that don’t make a product obsolete	0	0	0
a standard prioritizing 'higher' vs 'lower' criticality of materials	0	0	0

6) What will it take to overcome the social, economic, and political barriers to recycling? [IDEA]

Responses	Score	Upvotes	Downvotes
National or global standards rather than piece work standards per geo or state	4	5	1
Education	3	4	1
Commitment from senior government leaders	3	4	1
public education	1	2	1
Education of the populace.	1	2	1
Education	1	2	1
Better design	1	2	1
Global economic incentives	2	2	0
Money	2	2	0
incentives to end users	0	1	1
Level playing field for recyclers across the world	1	1	0
Consistent resources and education	0	1	1
investment in infrastructure	1	1	0
National electronics recycling requirement and increased use of purchasing power to drive change	1	1	0
New legislation	1	1	0
EPR policy, to make products reflect true cost of disposal/EOL management. That is now hidden from consumers, and exported by manufacturers	1	1	0
Reaching out to the people who don't think like us.	-1	0	1
Align incentives	0	0	0
Accessibility	0	0	0
John was right. Education	-1	0	1
Reaching out to people not open to education.	0	0	0
consistent funding for collection infrastructure	0	0	0
Make electronic recycling easy for consumers and businesses	0	0	0
Marketplace for reuse of materials	0	0	0
Determining the barriers to acceptance, cooperation.	0	0	0
More communication across value chain	0	0	0
more consistency across state and local lines	0	0	0
Quit trying to do the same things and expecting different results.	0	0	0
consumer education	0	0	0

7) Are there other challenges to electronics recycling that have not yet been discussed in this session? (e.g., more economic ways to identify and remove lithium ion batteries from electronics)

Response	Score	Upvotes	Downvotes	Comments to Response
Human behavior	5	5	0	
collection and transportation	5	5	0	
What if the electronics producers do not use metals anymore?	4	4	0	That seems unlikely to me. There are so many metals in electronics!
Bad actors	3	3	0	
Recycling Destruction Certificate	2	2	0	
Role of product design (designing products for easy disassembly and material recovery), Illegal trade, there is no proper data on the product end of life flows, how much is collected, recycled, reused in the U.S versus how much goes overseas	2	2	0	
best policy practices	1	1	0	
Too many non-reputable organizations posing as things they are not	1	1	0	
Global price floors for products	1	1	0	Recycling markets are worse than farming. If the bottom falls out of a particular product the recycler is screwed
How to establish a national marketplace enabling the full cycle from purchase to reclamation of a product	1	1	0	Systems thinking is needed that engaging all stakeholders from producer consumer recycler consumer.
Capitalism	1	1	0	
challenges to making low value scrap recycling profitable	1	1	0	
how to improve the leap from research to commercial scale	0	0	0	

Role of manf. And efforts at modularity. At end of day OEMs need to drive initiative but recognize they are businesses w financial obligations.	0	0	0	
The cost and inconvenience of recycling as labor goes up and prices go down.	0	0	0	
Lack of trust and greenwashing.	0	0	0	
Understanding why e-waste recycling is now only about 20%, and how to move it up.	0	0	0	

Session 2B: Battery Recycling Challenges

1) What is your role in battery recycling? (n=15)

   Producer/Manufacturer: 27 %
   Researcher: 27 %
   Government: 20 %
   Industry organization: 13 %
   Recycler: 7 %
   Other: 7 %
   Reuse/Repair: 0 %

2) What does a bad day look like at a recycling facility?

Responses	Score	Upvotes	Downvotes
Fire	0	0	0
fire	0	0	0
recordable injury	0	0	0
Fire.	0	0	0
empty front of line	0	0	0
A "thermal event "	0	0	0
Fire	0	0	0
Contaminants	0	0	0
Explosion/fire	0	0	0
Market for materials tanks	0	0	0
not enough batteries to recycle	0	0	0
Fire	0	0	0

3) How feasible is a second life for batteries as opposed to immediate recycling? (One star = not feasible at all, five starts = very feasible) (n=23)

1: 0 %
2: 22 %
3: 43 %
4: 17 %
5: 17 %

4) To what extent does lack of appropriate data impede your ability to be more circular? (One star = not impeded by lack of data, five stars = very impeded by lack of data) (n=21)

1: 0 %
2: 29 %
3: 10 %
4: 33 %
5: 29 %

5) What specific data would you benefit from? (e.g., LCA data for products, recycling operations and processes, materials content of products, etc.)

Responses	Score	Upvotes	Downvotes
Material content of battery	2	2	0
expected vehicle lifetime	0	0	0
materials content of products	0	0	0
End of life performance	0	0	0
Refurbished battery perf testing	0	0	0
Materials content	0	0	0
Cost - revenue data for different scenarios	0	0	0
who is consuming output from re-x operations	0	0	0
Materials content and availability of stock	0	0	0
Remaining health after first life	0	0	0
Downstream information and markets	0	0	0
Product flows	0	0	0
What second use customers are willing to pay	0	0	0
MSDS. reliable State of Health data	0	0	0
Expected performance changes	0	0	0
Technology comparisons	0	0	0
customer purchasing decision (new products) based on post-consumer content	0	0	0

6) What standards, either documentary or reference materials, would enhance recycling of batteries?

Responses	Score	Upvotes	Downvotes
Performance standards for recycled materials	0	0	0
Material purity for electrode use	0	0	0
Minimum performance standards	0	0	0
NIST Best Practice Guides on characterization for verifying performance	0	0	0
non-proprietary evaluation methods of battery health	0	0	0

7) What will it take to overcome the social, economic, and political barriers to recycling?

Responses	Score	Upvotes	Downvotes
Design for circularity	0	0	0
Consumer education	0	0	0
Incentives for recycling	0	0	0
Market pull and policy push	0	0	0
undeniable external risk	0	0	0
Design for circularity	0	0	0
Leasing model for EV batteries	0	0	0
Corporate commitment at high levels	0	0	0
Demonstration of safe economic process	0	0	0

8) Are there other challenges to battery recycling that have not yet been discussed in this session? (e.g., prevention of fire hazard)

Responses	Score	Upvotes	Downvotes
Standardization (it's a wild west now)	1	1	0
Materials export	0	0	0
Safety protocols at point of disassembly	0	0	0
Low collection rate	0	0	0
Trade policy	0	0	0
Increased collection rate	0	0	0
Reuse limited by cell degradation. Better data for degradation - remaining lifetime relationships and diagnostics	0	0	0
agree with speaker. scale.	0	0	0
Exports	0	0	0
design for circularity in large format batteries, particularly reuse. problems areas - welds connecting batteries, IP within the battery	0	0	0

Session 2C: Solar Panel Recycling Challenges

1) What is your role in solar panel recycling? (n=17)

   Researcher: 47 %
   Government: 29 %
   Recycler: 12 %
   Industry Organization: 6 %
   Producer/Manufacturer: 6 %
   Reuse/Repair: 0 %
   Other: 0 %

2) What does a bad day look like at a recycling facility?

Responses	Score	Upvotes	Downvotes
lead exposure	3	4	1
too much material and not enough markets	2	3	1
Equipment down.	2	2	0
Fire	1	2	1
run out of storage for recovered materials that have no economical market	0	1	1
no silver	0	0	0
too many different types of modules to process	0	0	0
Materials left outside without any containment, continuous fires during the recycling process,	0	0	0
Fire hazard	-1	0	1
Cookie plastics	-1	0	1
Mixing up elements	-1	0	1
The Machines stop working	-1	0	1
Contaminated land	-1	0	1
Covid outbreak	-1	0	1
Audit when you have a lot of material to recycle	-1	0	1
Sudden/unplanned increase in incoming waste volume, which is beyond the capacity of the plant.	-1	0	1

3) What specific data would you benefit from? (e.g., LCA data for products, recycling operations and processes, materials content of products, etc.)

Responses	Score	Upvotes	Downvotes
Accurate list of PV recyclers -- not resellers or brokers -- in the USA. The lists I've seen are really bad.	5	5	0
Location of recycling facilities and logistics information	4	4	0
weight fraction of materials in modules of different vintage, technology and manufacturer	2	3	1
Secondary market requirements for materials and market value	3	3	0
TCLP data	1	2	1
Inventory and process data for recycling. Material composition of panel.	1	2	1
LCA data for recycling processes	0	1	1
estimates of material use	0	1	1
Economic data such as the value of all components of the materials in today's market and recycling operations and processes	0	1	1
Origination of PV modules destined for recycling and why it is being recycled vs. other methods like reuse	0	1	1
RCRA TC data, as well as information about potential worker hazard data.	0	1	1
Where to recycle	1	1	0
LCA data	-1	0	1
LCA	-1	0	1
geospatially resolved (at least state level) projection of mass of materials (not just whole module mass) from projected end of life modules	-1	0	1

4) What standards, either documentary or reference materials, would enhance recycling of solar panels?

Responses	Score	Upvotes	Downvotes
prohibit solar panel disposal in dumps	4	4	0
regulatory compliance checklist for handling, transport, storage	4	4	0
sampling procedure for TCLP	0	1	1
R2 for sure. ISO 14001 and OHSAS 18001 as well.	1	1	0
Manufacturer takeback programs	-1	1	2
Material composition (like an ingredients list), even if generalized	0	1	1
Purity or amount of material required (cost efficient) to recycle	0	1	1
manufacturing standards that would support reuse/refurbishment/recycling. This could include fasteners/adhesives, for example	0	1	1
material composition of panel, reference to region specific recycling requirements and regulations	-1	0	1
State funded programs	-1	0	1
who is responsible for module recycling	-1	0	1
recertification of used modules for reuse in grid-tied settings	-1	0	1
Direct sales data from national solar installers - which residents, where, how many kw	-1	0	1
R2	0	0	0
Purity of recycling products	0	0	0
Labeling on PV products	0	0	0

5) What will it take to overcome the social, economic, and political barriers to recycling?

Responses	Score	Upvotes	Downvotes
Government Policy	4	5	1
Education	3	4	1
policy change	2	3	1
It's more economic than anything else. The intrinsic values of the PV modules continue to decrease as the cost to process/recycle them increases and the barriers to doing so also increase	3	3	0
Policy and technology	1	2	1
Policies and regulation	1	2	1
Decrease the barrier for end-users to recycle/reuse	1	2	1
Incentives to encourage / require recycling and penalties to discourage landfilling	1	2	1
acceptance of recycling as a cost of doing business	2	2	0
R&D funding	0	1	1
levelized, national regulation	-1	0	1
Make climate action education a requirement to: 1. graduate high school 2. Enter College 3. Graduate from college	0	0	0
increase social network learning about recycling	0	0	0

<u>Session 6: Breakout Session</u>

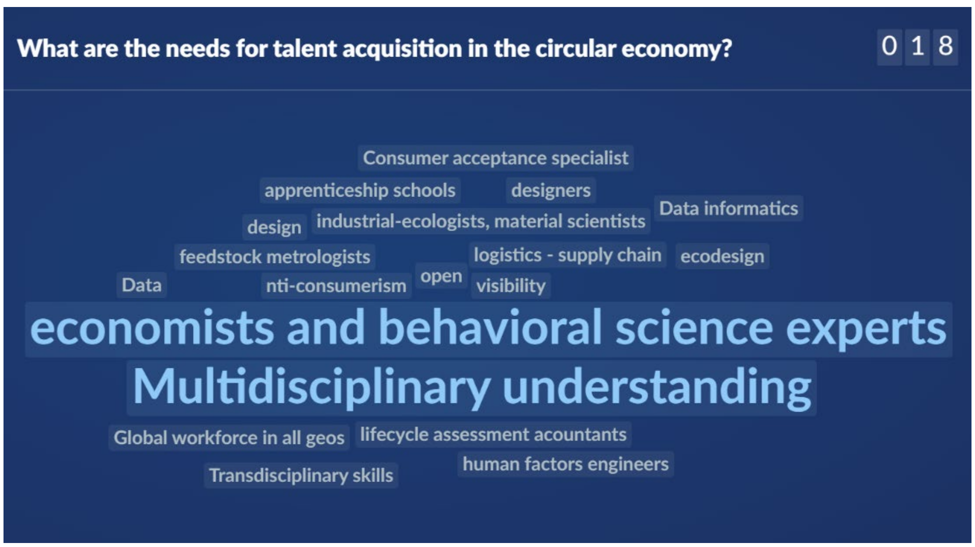
Enabling a CE

1) What are the appropriate metrics for a circular economy, and why?

Responses	Score	Upvotes	Downvotes
Decreasing purchasing of virgin products	3	4	1
modular and replace-able	2	2	0
% recycling	2	2	0
consumer behavior	2	2	0
reduction in footprint, measured by GHG emissions, toxics	2	2	0
Reduction in waste	1	1	0
Toxins	1	1	0
Materials, modularity, EoL and energy	1	1	0
Cost/mass of recycled material	1	1	0
percent returns	1	1	0
How much material winds up in landfill?	1	1	0
% of materials reused/recycled	1	1	0
Weight	0	0	0
energy intensity	0	0	0

cost parity to virgin	0	0	0
zero waste	0	0	0
% imported materials	0	0	0
Ingredients	0	0	0
%Mass coming out of use on total mass in use	0	0	0
recycling efficiency	0	0	0
data on waste- mass, content	0	0	0
real total cost of commodities/materials, incorporating cost of externalities	0	0	0
Total virgin raw material inputs (ex: total ore weight)	0	0	0
Environmental scientists	0	0	0

2) What are the needs for talent acquisition in the circular economy?



3) What types of standards and certifications would help facilitate circularity of solar panels, batteries, and electronic products?

Responses	Score	Upvotes	Downvotes	Comments to Response
trust in waste management	3	3	0	
Electronics - standardized reporting on materials in and materials out from recyclers	2	2	0	
standard for communicating material content, repair, refurb and recycling instructions	2	2	0	
solar panel recycling	1	1	0	
battery standards for 2nd life	1	1	0	
Battery mining for second use	1	1	0	
state of batteries	1	1	0	
certificate of data security	0	0	0	
standards to facilitate "generic" replaceable components that fit all manufacturer's products	0	0	0	Jurisdiction data will let us access broken panels, etc. before dump
Utility entities and licensing departments know who installs kW where, when, specifics use it	0	0	0	
Standards that characterize the condition of batteries and PV for the buyer	0	0	0	
Materials labels	0	0	0	
for solar panels - info on material content to determine if Haz waste at EOL	0	0	0	
Repair and construction diagrams, service manual	0	0	0	

4) What are data challenges and needs specific to the circularity of solar panels, batteries, and electronic products?

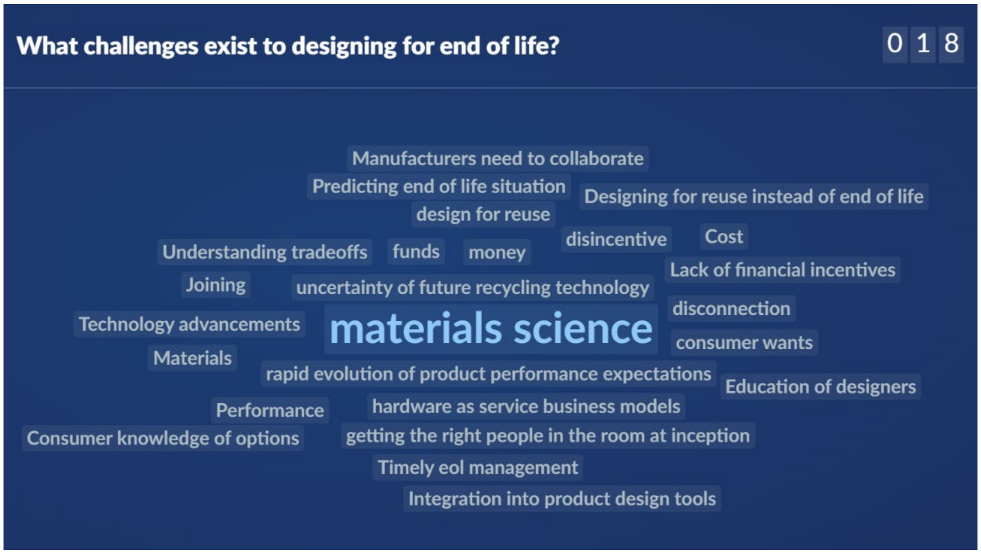
Responses	Score	Upvotes	Downvotes	Comments to Response
data on materials used in various products - either at the product level or component level.	4	4	0	
what is a battery's state of health needed for different applications	3	3	0	
Quantification of what materials are in each product and predictions for how this will evolve over time (solar panel 40 years ago is very different than one produced today)	3	3	0	
consistent battery state of health measurements	2	2	0	
Easily found data describing product composition (BoM and materials), and product description enabling disassembly.	2	2	0	
product life	1	1	0	
Jurisdictions know where panels are when installed; get to them before they enter waste stream	1	1	0	
where to send for refurbish/recycle, for next step after EOL	1	1	0	
standardizing data collection	1	1	0	
Information on what kind of ‘abuse’ can a system take. This could be weather, electric power quality	0	0	0	
quantifying dormant devices in storage	0	0	0	
For Li-ion batteries, need more information on how charge relates to potential to ignite, etc.	0	0	0	
relative footprint of materials to be able to evaluate material choices in design	0	0	0	across multiple modalities (toxics, EOL)
predictions on waste generation	0	0	0	
Characterization of connectors	0	0	0	
average use life	0	0	0	

5) How can tools such as life-cycle analysis and techno-economic analysis be enhanced or adjusted to better facilitate a circular economy?

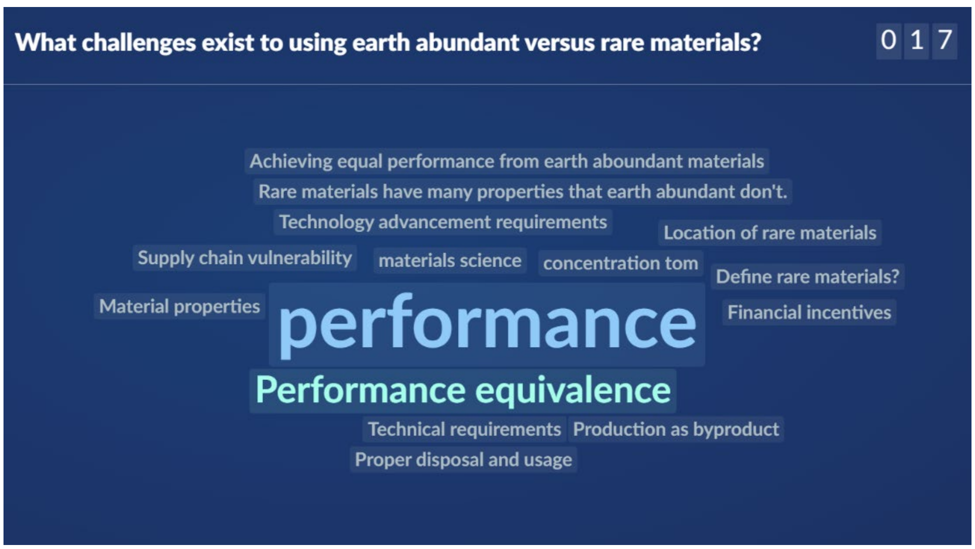
Responses	Score	Upvotes	Downvotes
Expand scope to include multiple product lives	4	4	0
actual materials composition	1	1	0
focus groups about why they trash stuff (fire damage, hurricane, luxury)	1	1	0
Transparency of current use in industry and governments	0	0	0
Integrate explicitly into all engineering programs around material and product design and manufacturing.	0	0	0
Boundaries for up a analysis	0	0	0
LCA are very expensive	0	0	0
assignment of a equivalent carbon cost value to products	0	0	0
Integrate with product design.	0	0	0
Better and more complete reliable cost and LCA data	0	0	0
be able to quantify reuse, repair, vs recycle pros/cons for a specific use case/market	0	0	0

Design

1) What challenges exist to designing for end of life?



2) What challenges exist to using earth abundant versus rare materials?



3) What is needed to increase the use of earth-abundant materials versus rely on rare materials?

Responses	Score	Upvotes	Downvotes
Performance	3	3	0
R&D to show feasibility	3	3	0
Incentives	2	2	0
investment in materials science for performance	2	2	0
Integrating sustainability early in tech development	2	2	0
Research	1	1	0
Research and development	1	1	0
Education of designers	1	1	0
materials research	0	0	0
invention	0	0	0
Move away from Moores law	0	0	0
Change requirements	0	0	0
desired activity	0	0	0
scarcity is sexy	-1	0	1
identify key performance aspects and find cognates	0	0	0
incentives for designing products that avoid use of scarce materials	0	0	0
development mindset	0	0	0
high-throughput (simulation and experiment) methods to find substitute materials	0	0	0
Use less, get it back	0	0	0
Rare earth materials aren't really rare. It is more political as 90% comes from China. Expand US mining for these materials and move away from foreign dependency.	0	0	0

4) What challenges exist to using recycled versus virgin materials?

5) What solutions could help to overcome challenges to using recycled materials?

Responses	Score	Upvotes	Downvotes	Comments to Response
Design standards	5	5	0	
infrastructure of recycling facilities & transportation	4	4	0	
For batteries and electronics, better ease of removal of parts	3	3	0	
Better process	2	2	0	relative to purity - better process to recover more material
Standards	1	1	0	
standards around what must be reused	1	1	0	
consumer education	1	1	0	
Consistent supply	1	1	0	
incentives for using recycled materials	1	1	0	
Policy	0	0	0	
minimum required purity standards	0	0	0	
Better marketing to vain folks	0	0	0	
Better cost competitiveness for some materials	0	0	0	
Recycling process that doesn’t degrade material	0	0	0	

6) Is design for circularity in conflict with a capitalistic economy?

No: 75 %
Yes: 25 %

7) How can NIST facilitate design for a circular economy?

Responses	Score	Upvotes	Downvotes
standards for manufacturers, developed with industry	7	7	0
Promote standardization	5	5	0
Help harmonize data and study findings	4	4	0
Standards development support	3	3	0
Policies with incentives for circular design	2	2	0
policy influence	1	1	0
Hire Materials Science Students	1	1	0
Creating a list of materials and processes recommended for change	1	1	0
standards for evaluating products and materials	1	1	0
standards and best practices	1	1	0
help create global standards	1	1	0
develop sophisticated databases from the myriad that already exist	1	1	0
Standardized datasets	1	1	0
lead public awareness	1	1	0
Education	0	0	0
determine purity tolerances for post-consumer feedstocks	0	0	0

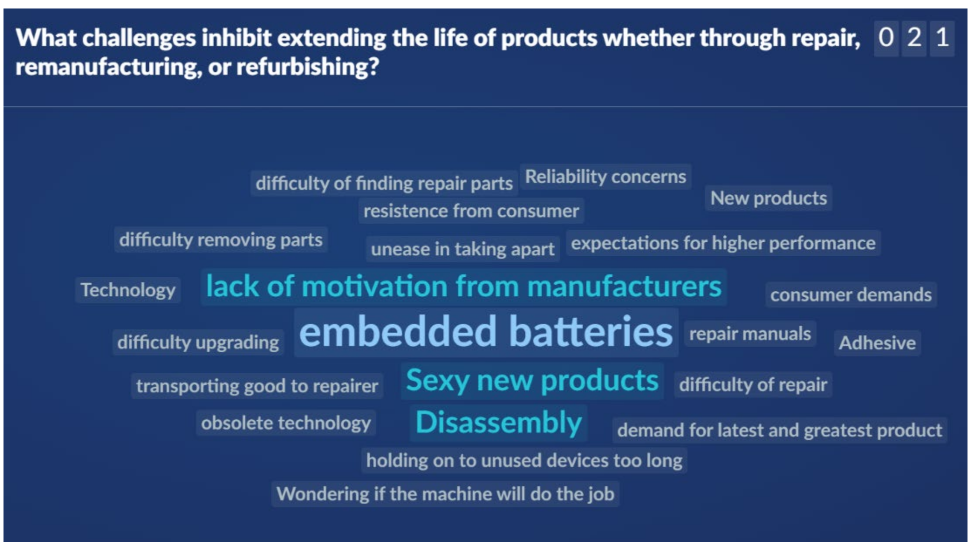
8) Are there other design challenges or needs that have not yet been discussed?

Responses	Score	Upvotes	Downvotes
Integration into product design	5	5	0
Reversible fasteners	1	1	0
rapid material composition fingerprinting	1	1	0
basic science topics that feed into the applications	0	0	0
How can IP be protected in a field where we want publicity	0	0	0
breaking manufacturer monopoly on components	0	0	0
design incentives	0	0	0
Insight into wil	0	0	0
Consumer behavior	0	0	0
Alternative to adhesives but maintain thin	0	0	0
Insight into EoL	0	0	0
Software	0	0	0
Cyber physical systems	0	0	0

Use/Reuse

1) What are challenges to ensuring the security of data on electronic devices during reuse?

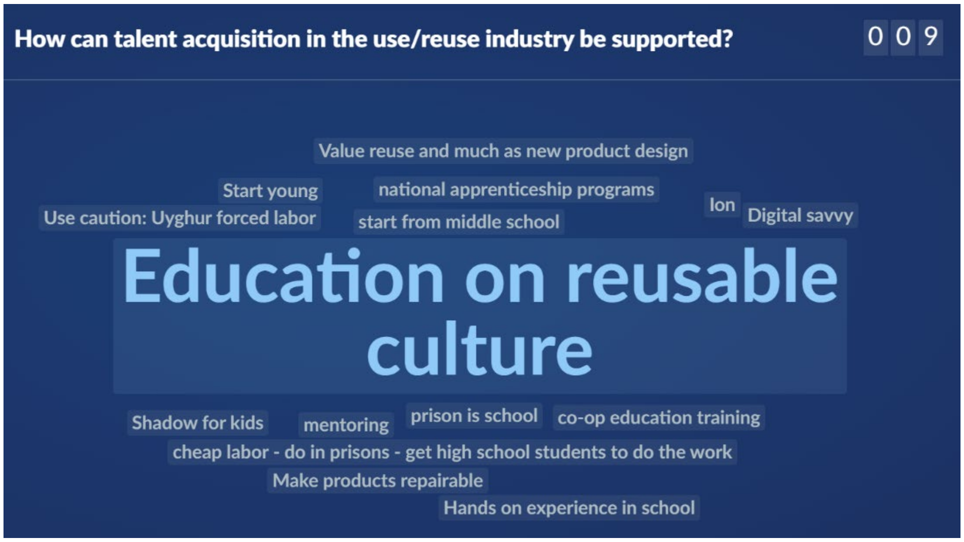
2) What challenges inhibit extending the life of products whether through repair, remanufacturing, or refurbishing?



3) What types of standards and certifications could help extend use/reuse?

Responses	Score	Upvotes	Downvotes
assembly/disassembly standards	5	5	0
Performance standards	4	4	0
standards that support easily swappable batteries	3	3	0
Best practices for disassembly	2	2	0
standards for assessing state of spent batteries	2	2	0
Standards for measuring circularity	2	2	0
Performance standards that must be certifiably met	1	1	0
qualification of which materials must be attempted reuse	1	1	0
battery state of health standards	1	1	0
standards for measuring reliability durability, to reward	1	1	0
lifetime standards	0	0	0
continue servicing old stuff	0	0	0
public disassembly guides	0	0	0
repairability index	0	0	0
expected lifetime certification	0	0	0
Lifelong	0	0	0
Policy of providing repair instructions	0	0	0
Battery discharge and safety	0	0	0
Guidelines to manufacturers around repair instruction	0	0	0
Don’t forget the function of software in usability (security patches)	0	0	0

4) How can talent acquisition in the use/reuse industry be supported?



5) How can secondary markets for used/repaired/refurbished products be expanded?

6) What are other challenges and needs for extending the use/reuse of solar panels, batteries, and electronic products in the circular economy?

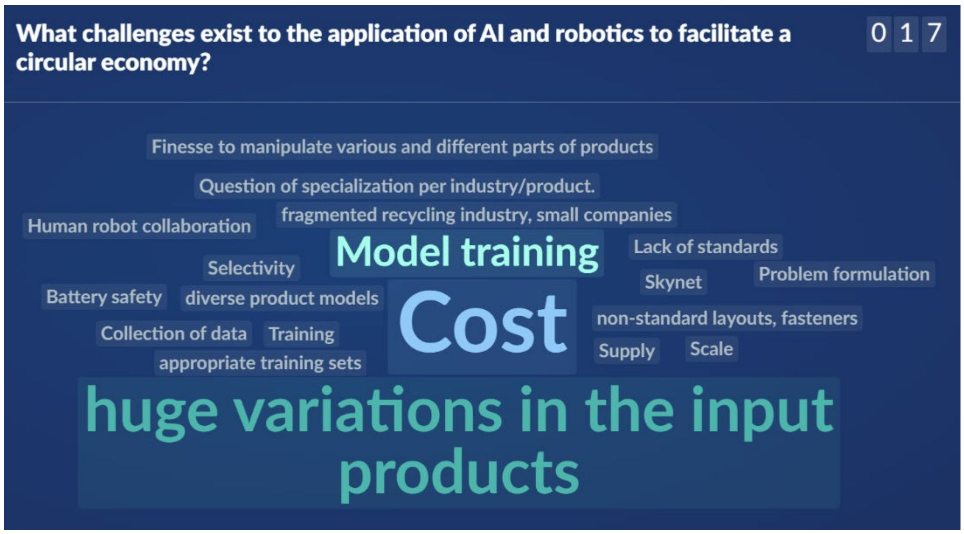
Responses	Score	Upvotes	Downvotes
No consistent signal for producer responsibility	4	4	0
Fractured regulatory/solid waste framework in US	3	3	0
access to collection	3	3	0
incentives for recycling	2	2	0
standards for repair and certification standards for afterwards	2	2	0
greater collection efficiencies	1	1	0
The breakdown of the Panels for Recycling that are profitable	1	1	0
safe collection of batteries	1	1	0
Insufficient supply in growing market	0	0	0
international trade	0	0	0
We need to reach a point where advances in performance and technology has plateaued	0	0	0
Reduce exports	0	0	0
Reclamation practices	0	0	0
Utilize these products in countries/areas that don't have the luxury of new equipment.	0	0	0
Cost parity with new equipment	0	0	0
Profitability needs to be related to societal benefit	0	0	0
lack of consumer awareness	0	0	0
Reclamation practices	0	0	0
more collection sites	0	0	0
Policy patchwork	0	0	0
Manufacturing incentives for reclamation	0	0	0
Economies of scale	0	0	0
Information standards for supply chains	0	0	0
Test equipment	0	0	0
Material dispersion	0	0	0

EoL management

1) Should AI and robotics be employed in the EOL management of: (n=18)

    Batteries: 6 %
    Electronics: 6 %
    Solar Panels: 0 %
    None of the above: 0 %
    All of the above: 89 %

2) What challenges exist to the application of AI and robotics to facilitate a circular economy?



3) Which entity/group should have roles in accountability for End-of-Life management? (n=21)

    Manufacturer: 29 %
    Owner: 5 %
    Regulatory entities: 0 %
    All of the above: 67 %

4) What challenges inhibit the effective collection of devices for proper EOL management?

5) What challenges impede the sorting and disassembly of devices? If speaking specifically about a product type, please identify.

Responses	Score	Upvotes	Downvotes
Embedded batteries	7	7	0
complexity of structure - proprietary build	5	5	0
Disassembly is not taken into account as part of the design	5	5	0
no standard labeling of batteries	4	4	0
Instruction	3	3	0
Adhesives	3	3	0
Material ID and composition	3	3	0
Irreversible fasteners	2	2	0
Adhesives	2	2	0
glued parts	2	2	0
Glued in batteries	2	2	0
Lack of labeling	2	2	0
Electronics - huge variation of designs	1	1	0
Electronics - time lag when returned	1	1	0
No labels	1	1	0
Lack of design knowledge	1	1	0
Glue	1	1	0
Warranty from OEM	0	0	0
diverse models	0	0	0
Big Battery found solutions	0	0	0
Miniaturization	0	0	0
compact design	0	0	0
Silicon on the part	0	0	0
battery modules - welding, adhesives impede recycling individual cells	0	0	0
Sometimes model numbers must be read, and if they aren't present ...	0	0	0
Varying design	0	0	0
Lack of will	0	0	0
perceived lack of value	0	0	0
lack of labels	0	0	0
Weak supply chains	0	0	0
Lack of information on material	0	0	0
Business case	0	0	0
Roi	0	0	0

6) What are solutions or needs to overcome these challenges?

Responses	Score	Upvotes	Downvotes
Design for disassembly	8	8	0
Design for ease of disassembly	5	5	0
Material Labeling	4	4	0
optical sorting using QR codes	4	4	0
Design products with disassembly in mind. Perhaps with incentives.	3	3	0
infrastructure (network) of disassembly facilities & local training	2	2	0
Business case	2	2	0
Best Practice Guides that support "Right to Repair' rules from other agencies or disassembly requirements?	2	2	0
Community action	1	1	0
labels	1	1	0
Blockchain	1	1	0
Assembly manuals	1	1	0
stable funding for recycling programs	1	1	0
labels	1	1	0
Monetize sustainability	1	1	0
Material spec	1	1	0
Standardized designs	0	0	0
Materials Specs when materials come from another country	0	0	0
Manufacturer transparency	0	0	0
Embed such information in the bar code when product is purchased	0	0	0
instruction videos on YouTube	0	0	0
tax products of low circularity	0	0	0
web dereferenceable id on data carrier on product	0	0	0
Value proposition	0	0	0

7) What are other challenges or needs for effective end-of-life management of solar panels, batteries, and/or electronic products?

Responses	Score	Upvotes	Downvotes	Comments to Response
Toxic material	6	6	0	
How to keep supply chain consistent.	2	2	0	
OEM interest	2	2	0	
the overlap between metals and polymers recycling/end of life	2	2	0	
Materials marketplace	2	2	0	
Import and export controls on reused/recycled materials	1	1	0	
Have you discussed block chain?	1	1	0	
For Li-ion batteries, how to address the fire issues	1	1	0	
Specs on all materials that are being used	1	1	0	
Reclamation supply chain	1	1	0	
Economical technologies for materials recovery	1	1	0	
The need for circular to also be sustainable. Purchasing a service, does not mean, for instance, that the service provided involves sustainable products.	1	1	0	
Blockchain as distributed ledger for tracing material requirement and reducing fraud	1	1	0	
connection with basic science	0	0	0	
Building global capacity	0	0	0	
hazmat training	0	0	0	
Policy	0	0	0	
Infrastructure investment	0	0	0	
Board level disassembly and component harvesting.	0	0	0	Circuit board level that is
Material marketplace	0	0	0	
Incentives	0	0	0	
not sure; but googled block chain and circular	0	0	0	
OEM leadership	0	0	0	
is it true that renewable energy electrons have serial numbers. If so, each product should be connected thru block chain	0	0	0	
Continue to push for newer technologies like lithium iron phosphate batteries which will be inherently safer	0	0	0	