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SHORT COMMUNICATION

Circular Economy in a High-Tech World

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Abstract
The proliferation of electronics, batteries, and solar panels in recent decades has resulted in a substantial generation of "high-tech" end-of-life products. Currently, these products follow a largely linear model, i.e., extract → make → use → dispose, but significant effort is underway to transition to a more circular economy in which products and materials are kept in the economy and out of landfills, incinerators, and the environment. However, many technical and economic challenges can impede, constrain, and preclude a circular economy for high-tech products. The US National Institute of Standards and Technology recently convened expert stakeholders in a virtual workshop to identify key challenges and needs to foster a circular economy for electronics, solar panels, and batteries. Here, we discuss several of these challenges and needs, and provide specific data, standards, tools, proposed research and development, and educational needs to address them. Furthermore, we argue that a circular economy cannot be achieved by individual efforts alone, but rather necessitates collaboration across disciplines, industry sectors, public and private stakeholders, and geographical regions.

Keywords Circular economy · Electronic waste · Reverse logistics · Recovery · Recycling

Introduction

Shifting from a Linear to a Circular Economy

The traditional life of high-tech products such as electronics, batteries, and solar panels has followed a largely linear path, where materials are extracted, manufactured, used, and then disposed, typically in either landfills or incinerators [1, 2]. But interest and momentum are growing for a transition to a circular economy (CE) with the aim of minimizing the extraction of natural resources and maintaining the value and utility of materials already in the economy through reuse, repair, remanufacturing, and recycling [3]. Effectively and efficiently transitioning to a CE necessitates a complete understanding of the current lifecycle of high-tech products as well as identification of barriers facing increased

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circularity and opportunities to overcome those challenges. With that intent, the United States National Institute of Standards and Technology (NIST) held a virtual workshop in January 2021 entitled “Circular Economy in the High-Tech World” [4]. NIST is a US non-regulatory federal agency within the Department of Commerce created to promote US innovation and industrial competitiveness and support quality of life, and NIST’s Circular Economy Program works across material and product streams to keep atoms and molecules that make up products cycling within the economy and retaining their value [5, 6]. The workshop included presentations from 37 topical experts and participation from more than 275 attendees. Detailed information about the workshop can be found in [7]. This article provides a summary of the key outcomes of the workshop including challenges facing increased circularity and opportunities to address barriers and foster a CE for high-tech products and materials therein.

Circularity of High-Tech Products

Electronic devices are proliferating globally, both through the continued production of existing products (e.g., mobile devices, computers, televisions) as well as the insertion of such devices 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 initiatives have increased production of renewable energy technologies and electric vehicles (EVs). For example, in January 2021, President Biden signed Executive Order 14,008: “Tackling the Climate Crisis at Home and Abroad,” committing to increase renewable energy production in the US and convert all federal, state, local, and tribal vehicle fleets to “clean and zero-emission vehicles” [8]. State and local governments are also implementing climate change policies and programs, further incentivizing renewable energy projects and vehicle electrification [9–11].

The proliferation of electronics, solar panels, and batteries leads to the generation of obsolete products. Electronic waste (e-waste), defined as discarded electronic products powered by either a battery or plug, constitutes the fastest growing component of the municipal waste stream in the USA, and according to the Global E-Waste Monitor this has become an emerging problem worldwide [12, 13]. It is estimated that 53 million metric tons (Mt) of e-waste was generated globally in 2019, up 21% in just 5 years [13]. Americans alone create nearly 7 Mt of e-waste annually, an average of roughly 20.9 kg per capita per year [14, 15]. Currently, a mere 15% of e-waste generated in the USA is collected for recycling [15].

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 [16, 17]. 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 [18]. The USA alone is estimated to generate a cumulated 10 Mt of PV waste by 2050, second only to China [16]. That said, economic incentives such as the Solar Investment Tax Credit [19], combined with improved conversion efficiency of modern panels, may result in premature panel replacement, and thus lead to greater generation of PV waste in the near term [20, 21]. Crystalline silicon (c-Si) modules currently represent more than 90% of the global PV market but 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 [16].

Batteries are increasingly used for stationary energy storage as well as large- and small-format mobile applications. Lithium-ion batteries (LIB) are in high demand compared to other chemistries, particularly for electric vehicle (EV) applications, due to their high voltage output, long lifespan, low weight, resistance to self-discharge, durability at elevated temperatures, compact design, and low environmental risk [22, 23]. In the USA alone, 46 million passenger EVs are anticipated to be on the roads by 2035 [24]. Thus, the application of EV LIBs is expected to increase from 250 GW-hours in 2020 to approximately 1700 GW-hours in 2030 and 5000 GW-hours in 2050 [25]. LIB production estimates have posed concerns regarding resource availability and price increases of lithium and transition metal elements including cobalt, nickel, and manganese [26, 27]. 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 [26]. Based on these projections and lifespans, market analysts estimate that 1.2 Mt of batteries will reach end-of-life (EoL) in 2025 and rise to 3.5 Mt in 2030, a seven-fold increase over the 2020 disposition rate of 0.5 Mt [25].

The composition of electronics, solar panels, and batteries are increasingly complex. While exact data on the material content of specific devices is scarcely available (see for example [28]), it is known that many elements from the period table are utilized in devices, including precious metals and critical raw materials, as displayed in Fig. 1 [13, 29]. 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, in fact, not rare in the Earth's crust, although usually not found concentrated in mine deposits. Precious metals are generally the rarest elements in the Earth's crust and are also considered critical given their use in technology and limited geopolitical availability [30]. Critical minerals are generally identified by national governments (e.g., US Department of Interior [31], European Commission [32]) based on their importance to the economy and national security [33].

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. Similarly, solar panels and batteries contain an intricate mix of material

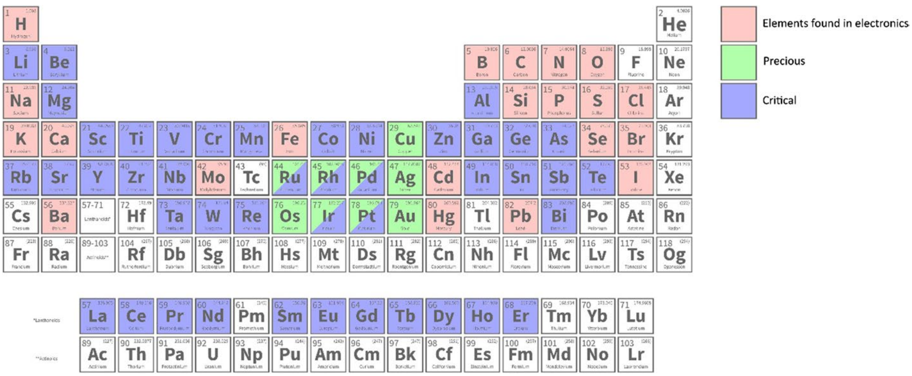

Fig. 1 Elements used in electronic products, calling out precious and critical materials (adapted from [13, 31])

components, many of which require high purity (e.g., solar grade silicon is at least 99.9999% pure) [16]. 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 [30]. That said, cobalt has been identified as an element of concern in the production of LIBs due to diminished reserves predicted due to cumulative world demand for batteries coupled with concerns about child labor in the Democratic Republic of the Congo, where most cobalt is mined [26]. This concern has driven EV battery manufacturers to adjust chemical formulations to rely less on cobalt and more on nickel. Table 1 presents typical material composition ranges of electronics, solar panels, and batteries. It is evident that many different compositions and chemistry options are present in modern devices, which continues to change with new generations. This variability and uncertainty pose a significant challenge for recyclers (discussed further in the "Barriers to a Circular Economy for High-Tech Products" section).

The increased production of high-tech products, and their associated material values represents a significant opportunity for recovery. The material value of e-waste alone is estimated at $62.5 billion, three times more than the annual output of the world's silver mines [37]. Certain metals, such as gold (used in cell phones and PCs), are present in high concentrations (~280 g per metric ton of e-waste, roughly 100 times higher than that of gold ore [13, 37]). Furthermore, harvesting the resources from EoL products generates substantially less carbon emissions than their 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 and components brings an even greater economic and environmental benefit. Therefore, as shown in Fig. 2, in a CE, the product lifecycle becomes much more efficient and closed through the reuse, repurpose, repair, remanufacture, and refurbishment of equipment and components, and recycling of materials at EoL. The circles of Fig. 2 are prioritized from the inside out to maintain the value of products, components, and materials in the economy for as long as possible, thereby minimizing the generation of waste [38].

Public and private organizations at the local, national, and global scale are advocating for increased circularity to reduce supply chain disruptions, address climate change, conserve resources, and reduce pollution. For example, the US Government has provided support for strengthening America's supply chains, revitalizing domestic manufacturing, and supporting recycling and reprocessing of minerals domestically [39–41]. Additionally, in 2021, the US Congress passed the Infrastructure Investment and Jobs Act [42], a bill that, in part, provides $60 million for research into battery reuse and recycling, $50 million for state and local governments to assist in the establishment or enhancement of battery collection, recycling, and reprocessing programs, and $15 million to retailers to fund battery collection programs for reuse, recycling, or proper disposal. The bill also calls for the creation of guidelines for voluntary battery labeling, the identification of best practices for battery collection and recycling, and the creation of a task force to develop an extended battery producer responsibility framework.

Aside from the Infrastructure Investment and Jobs Act of 2021, no federal statutes or regulations expressly mandate or incentivize the recycling-based recovery of EoL electronics, batteries, or solar panels. That said, several state- and industry-led policies have emerged. Currently, 25 states have some form of legislation aimed at promoting e-waste recycling and/or prohibiting disposal in landfills and incinerators [43]. Five states currently have enacted laws that address solar panel recycling, some allowing EoL solar panels to be managed as universal hazardous waste, and thereby necessitate

Table 1 Material composition of high-tech products (content % wt/wt) (adapted from: [13, 34–36])

Electronics, %		Solar panels, % (typical c-Si and thin film modules)		Batteries, % (typical LIB cell compositions[2])	
Iron and Steel	8–50	Glass	76–97	Cathode material: (includes lithium, cobalt, nickel, manganese, aluminum, iron, phosphorus, oxygen)	30.4–40.1
Aluminum	0.8–4.7	Plastic	4–10		
Copper	13–35	Aluminum	7–8		
Nickel	0.002–2.6	Silicon	5	Graphite	13.8–22.0
Zinc	0.2–8.2	Copper	1	Carbon black	1.7–2.7
Lead	1–4.2	Silver, tin, lead	< 0.1	Binder: PVDF[3]	2.7–3.6
Gold	0.008–0.1	CdTe and CIGS panels[1] includes other metals: (e.g., nickel, zinc, gallium, indium, germanium, cadmium, tellurium, selenium)	< 1	Copper	14.5–16.9
Silver	0.20–0.33			Aluminum	7.5–8.4
Plastics	20.6–23			Electrolyte $LiPF_6$	2.2–3.3
Glass & ceramic	2–33			Electrolyte EC	6.0–9.4
Wood	2.6			Electrolyte DMC	6.0–9.3
Rubber	0.90			Plastics	2.3–2.5

[1] *CdTe* cadmium telluride, *CIGS* copper-indium-gallium-(di)selenide; both are thin-film technologies

[2] Includes *NMC*, lithium nickel manganese cobalt oxide [NMC(111), NMC(622), NMC(811)]; *LCO*, lithium cobalt oxide; *NCA*, lithium nickel cobalt aluminum oxide; LMO: lithium manganese oxide; and LFP: lithium ferrous phosphate

[3] *PVDF*, polyvinylidene fluoride; $LiPF_6$, lithium salt; *EC*, ethylene carbonate (solvent); *DMC*, dimethyl carbonate

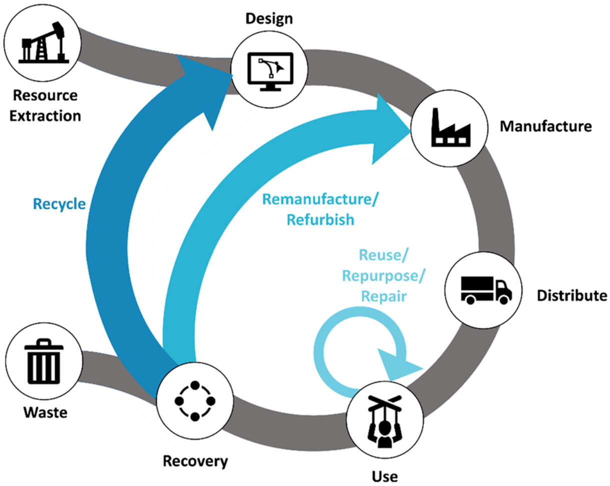

Fig. 2 Circular economy system diagram displaying mechanisms to close the lifecycle of materials and products

less stringent handling, transport, and storage requirements [44, 45]. Two states have policies that directly address reuse and EoL management of large-format LIBs, although some states have proposed bills under consideration [24].

Two accredited certification standards exist to support responsible electronics recycling: the Responsible Recycling ("R2") Standard for Electronics Recyclers [46] and the e-Stewards® Standard for Responsible Recycling and Reuse of Electronic Equipment ("e-Stewards®") [47]. Both programs establish auditable standards for e-waste recycling including safety, data security, and environmental performance that maximize reuse and recycling. At the time of this publication, 694 US recyclers held R2 certification, and 1411 are e-Stewards certified [48, 49]. R2 is reportedly considering the addition of PV panels in a future update [50].

Another certification supporting circular high-tech is the Electronic Product Environmental Assessment Tool (EPEAT). EPEAT is a global Type 1 ecolabel for information technology (IT) that helps purchasers, manufacturers, resellers, and others procure and sell environmentally preferable electronic products [51]. Covered products include computers and displays, imaging equipment, mobile phones, servers, televisions, and photovoltaic modules and inverters. Wearable devices will be included in the revised certification expected in 2022. EPEAT-registered products must meet environmental performance criteria that address material selection, supply chain greenhouse gas emission reduction, design for circularity and product longevity, energy conservation, EoL management, and corporate performance.

Advancements have also been made across industry to foster a CE for high-tech products. The increased trend of smart automation, digitization, and robotics in manufacturing processes (i.e., Industry 4.0) has resulted in more energy and resource efficient processes and circular business models [52, 53]. These approaches have also been used in the waste management industry to digitize and employ robotics in the collection, sorting, separation, and recycling of waste, including EoL high-tech products [54]. For example, the electronics manufacturer Apple has developed an industrial robot capable of disassembling different versions of iPhone cellphones, sorting components for reuse [55]. Similarly, researchers at the Danish Institute of Technology have been developing a robotic-based system that uses Artificial Intelligence to sort hazardous waste as part of the Adaptive Automated

Waste Electrical and Electronic Equipment Sorting Battery Extraction (AAWSBE1) project [54, 56]. The system aims to sort batteries in electronic devices and works with signals from different cameras and deep learning technology.

Although significant progress has been made in the transition to a CE, many social, technical, and economic barriers inhibit the adoption or expansion of circular practices and the closing of the lifecycle of high-tech products [1, 2, 54, 57, 58]. The remainder of this article dives into barriers and needs to foster circularity of electronics, batteries, and solar panels, as described by speakers and participants in NIST's workshop. The next section provides a series of barriers identified in the workshop, including cross-sectoral barriers that span industries and lifecycle phases of products, as well as product and practice specific challenges. The "Needs and Opportunities to Facilitate a Circular Economy" section discusses needs to overcome those barriers, outlining specific data, measurement and modeling tools, standards, and research and development opportunities that, if implemented, will help foster a CE for high-tech products.

Barriers to a Circular Economy for High-Tech Products

Many barriers inhibiting circularity of high-tech products are "systemic"; i.e., they cross multiple sectors (e.g., manufacturing and EoL management), span lifecycle phases of products, and pertain to all product types (electronics, batteries, and solar panels). Others are product specific or affect the practice of reuse, repair, refurbishment, or recycling specifically. This section describes the different categories of barriers facing circularity.

Systemic Barriers

The lack of harmonization of data, terminology, metrics, and modelling tools and approaches inhibit the consistent and unified adoption of CE practices across all sectors and product types. Data and information sharing is necessary to enable stakeholders throughout the supply chain and product lifecycle to implement circular practices. For example, data pertaining to the material composition, form factor, and history of a product or component are essential to determine the circular path at EoL. Furthermore, designers require information about the EoL processing of products to better design for repair, remanufacture, and recycling. Currently, systems to support recovery, reuse, and recycling are hindered by the lack of available data specific to materials, products, infrastructure, and markets. Without quality and available data, it is not possible to reduce the industry's environmental footprint, design effective policy, or drive social change for circularity.

Inconsistent nomenclature and terminology related to CE across sectors and industries means stakeholders are not speaking the same language. Terms such as "waste," "recycling," and "reuse" are ambiguous across sectors and countries and need further clarification. This is especially important to facilitate the international trade of second-hand, remanufactured, and recycled products and materials [59]. Harmonized terminology is therefore necessary to foster consistency and reliability across the CE and to support effective decision-making and policy.

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), agent-based modeling, and risk modeling frameworks are all examples of such tools [60–63]. To date, these tools have largely focused on materials and material processing loops that are often based on outdated or incomplete data. For example, effective modeling of mineral stocks and flows in the USA, such as cobalt, copper, and tantalum, is challenged by lack of available data [64–66]. Similarly, lack of available sales, lifespan, and disposition data inhibits the tracking of products throughout their lifecycle and EoL projections [67]. Increased development and coordination between modeling and assessment tools (e.g., LCA and TEA) are necessary to effectively understand 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 also a key barrier facing EoL recovery and recycling of high-tech products. While the generation of electronics, batteries, and solar panels is rapidly increasing, these products contain progressively lower concentrations of high-value metals (e.g., precious and critical metals). This “dematerialization” results in the dilution of high-value materials in products distributed globally, making recovery more challenging and expensive [68]. This directly affects the value of the secondary materials stream, which is driven by the mass of bulk metals (e.g., copper, steel, and aluminum) and precious metals [68, 69].

The traditional approach to product design is currently a barrier to a CE but needs to be part of the solution. Design plays a major role in the lifecycle and EoL recovery ability of electronic devices, batteries, and solar panels. Modern products are designed for functionality and performance, with little consideration for reuse, repair, or recycling. Manufacturers regularly release new models that are not only thinner (and therefore dematerialized), but also slightly more powerful and smarter than previous versions. These design changes frequently result in devices that are more difficult to upgrade or maintain. For example, batteries are now commonly glued into mobile phones to save space, but this limits the functional lifetime of the phone to that of the battery, often the only component with an inherently short life [70]. This also challenges disassembly for recycling as batteries must be removed prior to shredding (see the “Electronics Recycling Challenges” section).

Infrastructure to support a CE for electronics, batteries, and solar panels is limited in the USA. Collection of high-tech products at EoL is challenging 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 current lack of recovery infrastructure, whereas battery collection and transport are challenged by safety concerns due to potential LIB ignition. Furthermore, conventional recycling of high-tech products involves bulk materials recovery via a shredding model. While this practice recovers high-content materials such as glass, aluminum, steel, and copper, it could be optimized to also recover high-value materials such as precious and critical metals (i.e., materials with greatest supply chain concern), or materials of the purity necessary for reintroduction back into high-tech supply chains (e.g., solar grade silicon).

The lack of a trained, experienced workforce also inhibits a CE for high-tech products. While automation and the use of robotics is increasing in some sectors of the CE, typically in electronics recycling, manual labor will likely always be required to disassemble, test, repair, and evaluate parts and products. Manual labor is also necessary for battery identification, assessment, decommissioning, and material recovery. Additionally, metal 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, concerns over the exposure to hazardous materials, and lack of educational and training programs focused on this sector.

Barriers to Reuse, Repair, and Refurbish

High-tech products entering the market are increasingly complex, integrated, and compact, and therefore more difficult to disassemble for repair or refurbish. Current product design and manufacturing processes (e.g., use of glues versus screws) render rapid disassembly challenging, if not impossible. In addition, every year, new products and models are introduced, which repair and refurbishing operators must reverse-engineer to understand and fix. Information and materials necessary for product repair, such as service manuals, parts, software, and tools are often considered proprietary by manufacturers and are 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 manufacturer or their authorized vendors. Right-to-repair legislation (e.g., [71]) is intended to address this, giving consumers the ability to repair or modify electronic equipment by making available the product information, parts, and tools necessary for repair [72].

The lack of product standardization challenges circular decision-making. This is especially true for batteries, where different form factors, chemistries, and compositions make battery reuse and recovery difficult. For example, EV batteries no longer capable of powering vehicles may still be suitable for use in other applications such as grid storage. However, the diverse chemistries and forms of EV batteries challenge the configuration and assembly of battery packs in large-scale applications. Furthermore, the diverse arrangement of electronic products containing batteries slows the recycling process, as processors must open the device to locate and remove the battery prior to shredding. A standardized configuration would enable mechanical removal of batteries and potentially other components where shredding is undesirable (e.g., extraction of hard disc drives or printed circuit boards for targeted recovery).

This challenge is further exemplified by the lack of product and material labeling on high-tech products. Information necessary to support effective and efficient recovery is currently not provided on product labels. For example, as indicated previously, EoL processors must disassemble and reverse engineer devices to determine component characteristics (e.g., battery type), quality (e.g., presence of high-value materials), and configuration. As such, without effective labeling, EoL processors do not have the information necessary to determine the appropriate pathway (repurpose versus recycle) or downstream processor for equipment.

Product labeling deficiencies also inhibit consumers from understanding how best to procure, maintain, or manage devices at EoL. Current labeling schemes provide little information pertaining to the environmental impacts or CE features of a product (e.g., repairability, recyclability), thereby not providing consumers the ability to weigh such factors in the purchase of new equipment. Nor do labels guide consumers about how to use and maintain equipment for lifespan extension (e.g., battery charging routine to maintain battery health and longevity). Current labels also provide little information regarding how to recycle devices at EoL.

The economics of reuse, repair, and refurbishment are another barrier facing a CE. As new devices decrease in price, consumers tend to buy new products rather than pay for repair or buy a used device. Furthermore, concern about decreased performance or lifespan and the potential for future repair costs tend to prohibit the purchase of used products. In the case of EV LIB reuse for grid-scale energy applications, there is concern regarding the increased insurance costs associated with the use of second-life batteries. Also, often the most economical path for reuse is in other regions of the world such as China, India, and Africa, but export of high-tech products has been a cause for social and environmental concern, as importing regions may not have the technical capabilities or environmental protection policies to effectively recycle products at EoL [73–76].

Electronics Recycling Challenges

Every year thousands of new electronic products enter the market, and after some period of time inevitably reach EoL. Figure 3 depicts CE considerations for electronics, including several key challenges to recycling. One key hurdle facing the recovery of electronics is the actual collection of EoL devices for recycling. Many electronic products are “hibernating” in drawers and closets awaiting potential future use, repair, or resell, thus representing a significant volume of materials that is no longer used but has not yet been recovered [77]. Others are discarded in the municipal solid waste stream to be sent for landfill or incineration, likely due to concerns for data protection, or unawareness of alternative recovery options.

In the USA, electronics collected for recycling typically undergo bulk recovery through shredding. While some recyclers extract high-value components such as hard disc drives or printed circuit boards for targeted recovery, many insert whole devices into a shredder (after battery removal, if present) and the shredded fractions are then sorted into ferrous, nonferrous, and plastic material streams and sent for downstream processing. Bulk materials recovered therefore typically include plastics, steel, aluminum, and copper. The recovery of low-concentration metals from complex products, such as circuit boards or mobile phones, necessitates state-of-the-art metallurgically based recovery operations within an appropriate infrastructure. Facilities such as the integrated smelter-refinery facility at Umicore, Hoboken (Belgium), can recover pure gold and 16 other metals at high yields [78]. However, the overall recovery rates of the high-value, low-concentration metals depend on the effectiveness and efficiency of each stage prior to the metallurgical process: i.e.,

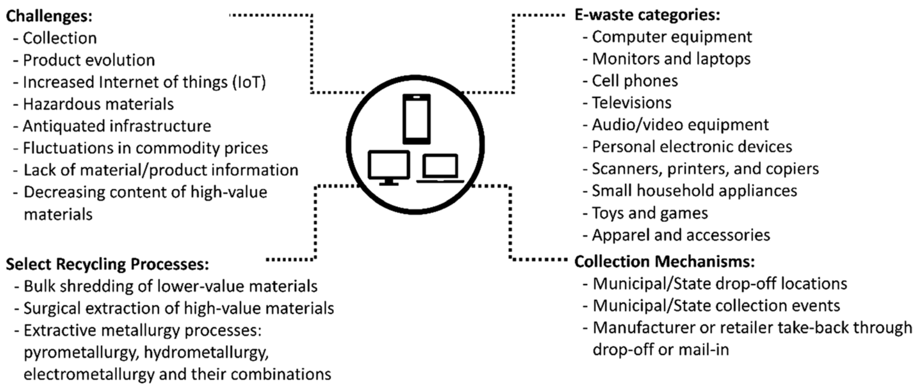

Fig. 3 Circular Economy considerations for electronics

low e-waste collection rates or high losses of metal fractions during dismantling and pre-processing significantly reduce recovery rates. In practice, due to such inefficiencies in the initial steps of the recycling chain, only a fraction of the recycling potential of metals is currently realized. For example, currently less than 20% of the gold recycling potential from European e-waste is recovered, where collection is considered the weakest part of the recovery chain [78].

The constant introduction of new models and equipment entering the market each year impedes the effective recovery of electronics. Thousands of new electronic devices and accessories enter the market annually, with diverse and changing shapes, sizes, material compositions, and material grades. Not only are new generations of common devices put on the market, such as cell phones, TVs, and laptops, but altogether new equipment (e.g., illuminated clothing and shoes, smart thermostats, etc.) are introduced and eventually reach the e-waste stream. 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 material recovery. Given the lack of information shared about products put on the market (as discussed in the "Barriers to Reuse, Repair, and Refurbish" section), recyclers must disassemble and reverse engineer devices to understand their component and material characteristics and determine the appropriate processing strategy. Furthermore, cars are now "computers on wheels" and household appliances such as washing machines and refrigerators are increasingly computerized. This increased IoT has introduced new products to the e-waste stream and forced the crossover of traditionally independent waste management sectors (e.g., automobile, textile, and large household appliance recycling) with e-waste recycling.

The increasing presence of LIBs in electronic products poses another challenge for recyclers. LIBs must be removed prior to shredding to prevent fires, and the removal process may require time-consuming and expensive manual disassembly. Safety also becomes an issue, as battery fires and explosions in recycling facilities are common. Therefore, reducing the risk of LIB-ignition greatly increases the difficulty of recycling electronics economically. The presence of hazardous materials in electronics poses another safety concern for recyclers. Toxic materials such as lead, mercury, cadmium, polybrominated flame retardants, barium, and lithium are present in electronics and may cause serious health problems if not handled carefully.

An additional challenge that has halted the growth of electronics recycling is industry's sensitivity to fluctuations in commodity prices for metals and other raw materials. Price swings for aluminum, copper, steel, and other secondary materials present significant challenges to business planning and impact the profitability of electronics recyclers.

Battery Recycling Challenges

The increased generation and evolution of mobile electronic products as well as EVs relies on LIBs of various shapes, sizes, form factors, and chemistries. Figure 4 presents multiple factors influencing the circularity of batteries, with a focus on EV LIBs. Unlike lead-acid batteries which are readily recycled, LIBs are composed of numerous materials including various transition metals in the cathode as well as graphite, aluminum, plastics, steel, and electrolyte solutions [79]. The configuration, size, and shape of LIB cells, modules, and packs differ from one manufacturer to another, and even from one model to another within a given manufacturer. Although most EV manufacturers use some configuration of pouch cells (flexible and lightweight soft pack), Tesla uses small cylindrical cells, like those used

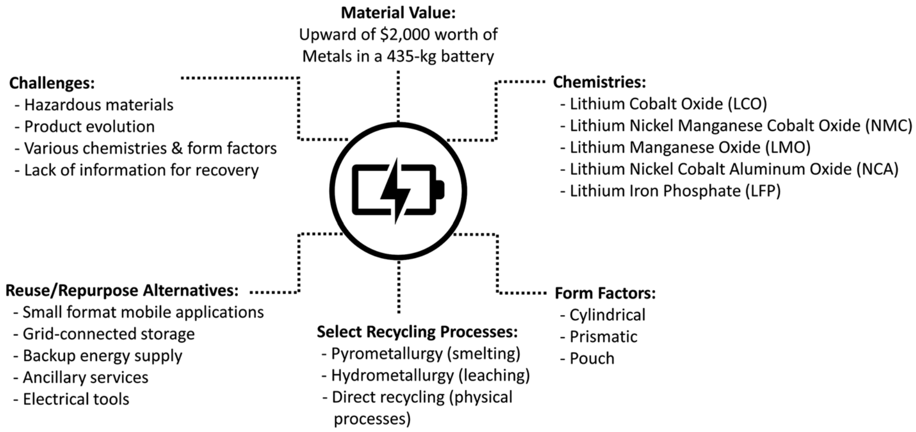

Fig. 4 Circular economy considerations for lithium-ion EV batteries (Sources: [26, 79, 80])

in many electronic devices [26]. The cells themselves also vary in their internal composition, in particular the cathode chemistry which can be any of a variety of lithium transition metal oxides (LCO, NMC, LMO, NCA, LFP, etc.). Many manufacturers are moving toward more nickel-rich compositions to reduce their reliance on cobalt [26]. The variability in LIB design and composition makes it difficult to develop a standardized approach to secondary use applications and efficient recycling processes.

The current battery recycling infrastructure is largely designed around processing small-format batteries from e-waste. However, projections estimate EV batteries will 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. Currently, there are three basic recycling process types: pyrometallurgy (smelting), hydrometallurgy (leaching), and direct recycling (physical methods) [26]. The latter is generally preferred from a CE perspective, as it requires fewer steps, less energy, and recovers more materials which can readily be used in new batteries. However, the recycling is challenged by the need to segregate battery inputs by cathode type, which require mechanical pre-treatment, as well as unknowns regarding the performance of recovered material in comparison to virgin material [23].

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 refurbished for reuse in EVs, repurposed (e.g., 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 or no information about batteries entering their facility, i.e., cathode chemistry, form factor, history (e.g., use cycles), or remaining charge. This hinders recycler's ability to choose the appropriate pathway for recovery. Additionally, the feasible reuse or repurposing of batteries is impeded by a lack of standardized performance metrics and safety and reliability testing for secondary use applications.

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, time frame for recovery, 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, limited publicly available information exists pertaining to the performance, quality, safety, and technical viability of reused batteries, which would enhance consumer trust and confidence and thus increase demand for reused batteries.

Solar Panel Recycling Challenges

There are four commercial solar module technologies available today, although crystalline silicon (c-Si) constitutes more than 95% of the global PV market and therefore currently represents the primary EoL panel type. As displayed in Fig. 5, there are reuse, repair, and recycling opportunities for PV panels, but they are challenged by many of the same barriers facing electronics and batteries: variability of cell and module structure, presence of hazardous materials (in this case heavy metals), decreasing concentration of high-value materials over time, lack of dedicated recovery infrastructure, and poor economics of recovery.

The low generation of waste PV panels to date means dedicated PV recycling facilities have not been economically justified, and thus the USA does not currently have a comprehensive solar panel collection or recycling infrastructure. As a result, only about 10% of EoL PV panels are currently recycled in the USA, while the remainder are likely sent to landfill or stored until alternative solutions are developed [83]. Today, most c-Si module recycling occurs in existing glass, metal, or e-waste recycling facilities, where they are run in batches when a sufficient module volume is obtained by the recycler [16]. Recyclers typically recover bulk materials such as glass and aluminum, and to some extent silver and copper, but fail to recover the semiconductor and other high-value or toxic materials such as tin, lead, or high-purity silicon. While technologies exist to recover metallurgical-grade silicon, improvements to recover solar-grade silicon (at least 6 N) would substantially increase the revenue potential of recycling. Additionally, current recycling processes do not separate the encapsulant layer of ethylene vinyl acetate (EVA), Si cells, and backsheet which are laminated to the glass pane, and thus the glass cullet recovered is not high-transmittance solar glass but rather lower-quality impure glass that cannot be used in the production of new PV modules. Furthermore, due to the presence of fluoropolymers in PV backsheet materials, the melting of glass cullet for the manufacture of new products necessitates a furnace scrubber to collect the fluorine that is released when melted [81, 84].

Significant research is underway to advance panel reuse and state-of-the-art PV recycling, but shortcomings persist that impede commercialization [16]. One key challenge is the variation of c-Si modules on the market. Module-level differences include 60 cells versus 72 cells, single-glass versus double-glass, framed versus frameless panels, among other variations. Within modules, PV cells can be monocrystalline or multi-crystalline, n-type

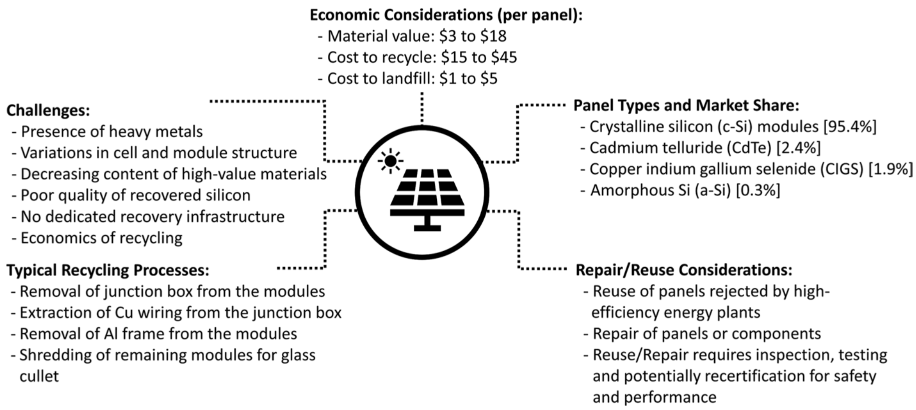

Fig. 5 Circular economy considerations for photovoltaic modules (Sources: [16, 81, 82])

or p-type, aluminum back surface field (Al-BSF) cells or passivated emitter rear contact (PERC) cells, whole cell or half-cut cell, unifacial or bifacial, contain different numbers of busbars, or have different wafer sizes [81]. This variation of cell and module structures lead to different module powers and efficiencies. Additionally, modules from different manufacturers often have different dimensions and weights. This challenges the reuse and recycling of PV panels, as modules of different power, efficiency, voltage, or current cannot be directly connected in series or parallel into a solar system due to mismatch losses. Recycling infrastructure and processes must be adaptable to all panel structures and material compositions.

Solar panels also have a complex material composition which includes low concentrations of high-value materials (e.g., silver, copper, and high-purity silicon) and thus an overall low material value per panel. This is compounded by the high cost of recovering the high-value materials. Currently, in the USA, the cost to recycle PV modules is around $15 to $45 per panel, significantly higher than the cost of landfill which is approximately $1 to $5 per panel [82]. Revenue from recycling is roughly $3 to $18 per module depending on the quantity and quality of materials recovered [81]. Further complicating the economics of recovery is the fact that the concentration of high-value metals is decreasing with panel evolution. For example, the use of silver in solar cells has declined by 70% since 2010 and is expected to continue to decline, with copper being the likely lower-cost replacement [16]. Furthermore, the trend toward thinner silicon wafers reduces the amount of silicon in each module. These trends in PV material composition pose a significant challenge to recycling economics.

Needs and Opportunities to Facilitate a Circular Economy

Needs to overcome the barriers identified above and to facilitate a CE generally fall into the following categories: collaboration; data and information harmonization and availability; agreement on metrics, frameworks, and tools; development of standards, specifications, and best practice guidelines; research and development; and education, outreach, and workforce training. Table 2 provides a brief overview of the requisites for each

Table 2 Requisites to advance a circular economy

Requisite	Description
Collaboration	Increased communications between stakeholders throughout the value chain and recovery system to promote system harmonization, information sharing, and feedback loops
Data and information	Harmonization, collection, aggregation, and increased access to material, product, market, and system level data and analytics
Metrics, frameworks, and tools	Increased development and coordination of metrics, models, and assessment tools to better measure, model, and evaluate CE advancements
Standards and specifications	Standardization of terminology, metrics, and model approaches; development of component and product standards; best practice guidelines for reuse, repair and recycling processes; and certification standards for reused and repaired products
Research and development	Basic and applied research aimed at material optimization, product design for recovery, and technology and process development for improved separation and recycling
Education, outreach, and training	Targeted information campaigns to educate stakeholders on appropriate actions based on role and sector of the CE. Training programs to support workforce development

category to advance a CE. This section provides specific opportunities for advancement in these areas which can impact circularity both on the short and long term.

Collaboration

Transitioning to a CE for high-tech products necessitates non-traditional, cross-sectoral collaboration. Increased communications between stakeholders throughout the lifecycle of products is essential to not only understand different dimensions and recognize the diverse perspectives and needs of various stakeholders, but also to distribute information and data in the development of feedback loops necessary for circularity. Innovative strategic partnerships including public–private partnerships are powerful tools for developing recovery systems, advancing design for circularity, promoting successful business models, and raising capital and financing for infrastructure. Collaboration can drive information sharing, organizational learning, and technology exchange, and thus requires trust and transparency. As such, communication channels that are participatory and inclusive must be enabled and supported. Collaborations must include the following stakeholders: equipment and component manufacturers; local e-waste collectors, haulers, and recyclers; metal reclaimers; resale, repair, and remanufacturing practitioners; global reuse end markets; researchers; academic institutions; industry associations; nonprofit and advocacy groups; and local, state, and national policymakers. This action underpins all other actions needed to facilitate a CE, because re-engineering the current linear system to a CE cannot be done by individual actors but rather requires a unified effort.

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 3 provides specific data needs identified in the workshop.

It is important that data be of high-quality, harmonized, standardized, and interoperable to enable effective utilization by stakeholders across domains and to facilitate data-driven innovation. Data distribution and sharing can take many forms. Abundant data already exists relevant to the CE, but sophisticated databases are necessary to aggregate and make available such resources. 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 (Findability, Accessibility, Interoperability, and Reusability) to ensure effective data discovery and usability across the CE [85]. Furthermore, standardized data documentation can take the form of actionable ontologies, an area with ongoing efforts at the international level (e.g., [86]).

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 recycling.

Information sharing requires transparency across product, market, and system levels. Transparent information exchange can enhance system performance, stimulate investment, and help strengthen stakeholder relationships throughout the lifecycle of products, thereby

Table 3 Data needs to facilitate a CE for high-tech products

Level	Data needs
Material level	Material stocks and flows in the economy Current and projected material demand/usage/consumption Hazardous material content and associated risk Change of material properties throughout lifetime
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

promoting circularity. Strategies are necessary to facilitate transparency and the open exchange of data and information while protecting proprietary information.

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 (e.g., lifetime) attributes of materials and products, and 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 the analysis of sustainability attributes across system levels (i.e., from product level to macro-economic level). Tools such as lifecycle assessment (LCA), techno-economic analysis (TEA), and material flow analysis (MFA) can provide a baseline for environmental impacts, identify supply chain vulnerabilities, and support cost–benefit analysis, policy evaluations, supply–demand scenarios, and economic feasibility studies. Results of these tools, especially LCA, need to be utilized in the production of new products, thus ensuring that sustainability considerations are deemed as important as product functionality and performance. However, to be applicable across the industry, these tools must be comprehensive, consistent, and transparent.

Standards

The development of standards is critical for the transition to a CE as they can provide harmonized, repeatable, and agreed upon guidelines, rules, or characteristics for activities or their results, and thereby aim to achieve an optimum degree of system order and consistency [87]. Standards relevant to a CE can be voluntary consensus standards, meaning they are developed in cooperation with all parties with an interest in the standard and that compliance is not regulated or mandatory. However, voluntary consensus standards carry significant weight, as they may be adopted widely and openly, written into contracts and agreements, and used to create federal policies and laws [88]. Furthermore, standards can be used to demonstrate regulatory compliance or fill regulatory gaps, increase transparency and trust among stakeholders and consumers, and support market development [89, 90]. Table 4 presents standards needed to facilitate a CE for high technology applications, and several are discussed in more detail below.

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 national and international public and private institutes and trade associations to reach consensus on definitions ranging from high-level concepts to technical details.

Standardization of components and product lines across product generations is also necessary to support consistency and reliability across the CE. In this sense, standardization means that no matter which manufacturer produces the product or component, they would all have the same characteristics, such as configuration, power, efficiency, voltage, current, dimensions, and weights. Standardization of components used in electronic products or PV systems (e.g., HDDs, batteries, junction boxes, inverters) allows for efficient repair

Table 4 Standards Needed to Facilitate a CE for High-Tech Products According to Lifecycle Stage

Focus	Description
Foundational	Definitions of terminology, concepts, and principles Specifications for metrics, measures, models, and tools Guidelines for the collection, storage, management, and accessibility of data and information
Design	Specification of component/product characteristics Guidelines to design for repair, refurbishment, recycling Guidelines for incorporating recycled content in products Guidelines for selecting materials that are safe for secondary use
Manufacture	Guidelines for responsible sourcing: e.g., renewable, recycled Guidelines for traceability of supply chain materials: e.g., digital transaction certificates Guidelines for persistent identification of materials Specifications for product EoL management labeling
Use, reuse	Guidelines for sustainable procurement Guidelines for proper data destruction/erasure Guidelines for decommissioning and safe handling of EV LIBs Guidelines for decommissioning of solar PV systems Specifications for quality and performance metrics for reuse Test methods for safety and reliability of second use products
Repair, repurpose, remanufacture (R/R/R)	Guidelines for decision-making of circular pathways for recovered materials/products Specifications for publicly availability repair information Specifications for the availability of replacement parts, tools, information Guidelines for R/R/R, including responsible party Test methods for safety and reliability of R/R/R products
Recycle	Specifications for product collection and recovery Specifications for recycled materials Guidelines for removing impurities during recycling processes
End of life	Guidelines for the proper disposal of CE waste materials

and refurbishment, as well as simplified recycling processes. Standardization of batteries, specifically battery chemistry, module, and cell structure, is also needed to support reuse applications as well as improve battery recycling. Similarly, standardization of PV cells and modules would improve their potential for reuse, repair, and recycling.

In the recycling sector, material quality standards need to be developed that specify the properties or characteristics of recycled materials. These can be used to ensure recycled materials are fit for re-entry into supply chains. The manufacture of many high-tech products necessitates a high level of material purity and an exact understanding of inputs to the production system, which are currently difficult to obtain from recycled materials. Quality specifications may help address this challenge by providing manufacturers the reliability and confidence necessary to utilize recycled-content feedstocks in the manufacture of new equipment. Such specifications could include metrics for material properties and performance, e.g., purity, strength, hardness, and other measurable physical and electrical properties that are important for manufacturing. Recycled content standards could further help to stabilize the markets for recycled commodities and reduce price volatility.

Best practice guides are needed to support the reuse, repair, refurbishment, and recycling of high-tech products. Such guides can include instructions about recovery processes as well as safe handling guidelines, thereby fostering environmentally and socially sound practices (e.g., worker safety), as well as promoting 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. Furthermore, a standardized process is needed for safety and reliability testing for secondary use applications. This entails the development of performance metrics and test methods to verify that reused, repaired, or refurbished products are safe and reliable. These methods could be included in certification standards to help positively impact consumer trust and confidence in second-use products. Such standards could, for example, certify an expected level of performance, lifetime expectancy, quality, safety, and technical viability of reused, repaired, or refurbished products.

Best practice guides pertaining to the efficient use and EoL management of devices would also be useful for consumers. For example, guidelines for efficient battery charging practices, data wiping/erasure, product assembly/disassembly, and battery handling and decommissioning could promote safe and effective reuse, repair, and recovery efforts on the part of consumers.

The standards identified above are generally developed by standard development organizations such as ASTM (American Society for Testing and Materials), ISO (International Standards Organization), UL (Underwriters Laboratory), and ANSI (American National Standards Institute). Some trade associations, such as ISRI (Institute of Scrap Recycling Industries) also create their own standards. Many, if not all, of these organizations are already developing CE-related standards.

Research and Development

Significant research and development (R&D) is needed to further propel the transition to a CE for high-tech products. Research needs range from high-level system analysis to scientific investigation and technology development. Specific research and development needs are presented in Table 5.

Much research is needed specifically for material recovery and recycling. Advanced, cost-efficient, and environmentally sensitive recycling processes need to be developed to

Table 5 Research and Development Needs to Facilitate a CE for High-Tech Products

Focus	Research needs
Materials science	Advancements in the reduction and/or replacement of critical and precious materials in future products Analysis of purity tolerances for recycled feedstocks
Manufacturing	Product/component digitalization and digital twins Development of a product and/or material traceability system (e.g., blockchain as distributed ledger for tracing material content and product life)
Recovery	Detection and separation mechanisms for the recovery of high-value, low-volume material constituents in existing products Advancement of artificial intelligence (AI) and robotics to identify, assess, and disassemble devices Rapid material identification Protocol development for assessing the state of spent batteries
System optimization and economics	Data interoperability across sectors Publicity of product materials/composition, while protecting Intellectual Property (IP) Economic assessments of recovery opportunities Cost/benefit tradeoffs of manual sorting, disassembly, and pre-processing Local employment and economic impacts of the recovery industry Economic benefits for county/region to collect and process high-tech products Markets for recovered and yet-to-be recovered material commodities
Consumer behavior	Current behavior related to consumption, usage, and EoL decision-making Perspectives about procuring secondhand, repaired, and refurbished devices Necessary motivators or drivers for behavior change

recover high-value, low-volume, and/or toxic materials from high-tech products. In other words, more advanced recycling methods are needed, beyond the current shredding and bulk material recovery model. There is no one-size-fits-all approach to recycling high-tech equipment, as each product category discussed in this article necessitates dedicated approaches and infrastructure. In particular, the recovery of critical and precious materials requires specialized processing including "surgical" extraction of certain components.

While significant R&D is currently underway, commercialization and scalability must also be economically feasible for long-term success to be realized. 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 speaks to the need for government-funded research and development in this field. Government-funded research and development could enable private investment in sectors of the CE by providing the data and information necessary to alleviate market uncertainties and thus prompt the development and deployment of cost-efficient reuse, refurbishment, and recycling processes.

Education and Outreach

Facilitating a CE necessitates education of all stakeholders associated with the manufacture, use, and recovery of high-tech products. Table 6 provides everal possible approaches to education and outreach activities that can help facilitate a CE for high-tech products.

Table 6 Education and outreach approaches to support high-tech circularity

Targeted audience	Education needs
Industry	Webinars and courses for transitioning from linear to circular business models Campaigns to instigate and foster information feedback loops between designers/manufacturers and EoL processors Training programs to support repair, remanufacturing, recycling workforce Certification programs in circular materials management
Academic	Lessons about material origin, use, and recovery and their environmental and social impacts Lessons about the consumers role in (un)sustainable consumption and link to climate change, biodiversity loss, resource scarcity, etc Lessons about recycling processes, role of design
General public-repair	Do it yourself (DIY) education for device repair Repair Cafes Information campaigns about secure data deletion/erasure Information campaigns about reuse, repair, remanufacturing opportunities
General public-recycling	Information campaigns about where and how to send EoL equipment for recycling Information campaigns about what happens to high-tech once they are donated or recycled

Workforce education and training of experts in the field of CE is also needed. Educational program development should aim to strengthen and enhance the technical and practical skills of a workforce prepared to support the increased recovery and recycling of high-tech products. Programs could produce expertise tailored to the needs for circularity, including materials design strategies, technology innovation for collection, sortation, separation, and recycling, or business development to keep materials in the economy. Furthermore, training programs should aim to promote the development of a skilled and distributed workforce focused on the growing field of circular materials.

Conclusions

A transition to a CE will support economic growth, provide reliable jobs, reduce the environmental impact of products, and enhance national security by reducing supply chain vulnerabilities. That said, many challenges must be addressed to facilitate circularity of high-tech products such as electronics, batteries, and solar panels. In this paper, we discussed many of the technological and economic barriers to a CE for high-tech products and provided specific data, standards, tools, research and development, and educational needs to address them. However, none of these opportunities can be performed in isolation. Economic, social, and environmental factors all contribute to the need for a CE, and thus transitioning away from a linear economy towards a more circular model necessitates collaboration across disciplines, industry sectors, public and private stakeholders, and geographical regions. Through this cooperation, we can reach an optimized CE that depends on reciprocity, trust, transparency, and cooperation between all players.

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Data Availability Recordings from the “Circular Economy in the High-Tech World” can be found at [4] and further documentation of the workshop can be found at [7].

Declarations

Competing Interests The authors declare no competing interests.

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