Rethinking circular economy for electronics, energy storage, and solar photovoltaics with long product life cycles

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Developments in recycling technology have largely focused on short-life-cycle products, such as plastic waste from packaging, consumer electronics, and construction debris, while complex, resource-rich, long-life-cycle electronic products, energy-storage, and photovoltaic components have been somewhat overlooked due to their intrinsic property of containing multimaterial in a complex manner. High-value products contain valuable elements, which are intricately incorporated and often lost at end of life. This article explores the need for a paradigm shift to a "product-centric" approach, which emphasizes the circularity of the whole product, with an emphasis on more focused ways of combining design and recovery methods. Opportunities for improved circularity include design for disassembly through modular approaches, development of materials for substitution, fabrication efficiency through novel selective synthesis of metals, high-throughput manufacturing of precision devices, and manufacturing processes that enable use of recycled materials for product. Design efforts should focus on current perceived limits in the degree of modularity, where parts can be made accessible for replacement and consumer uptake of recycled product.

Introduction

Innovations in material science and technology have led to the development of many feature-rich consumer product lines. These products are becoming increasingly agile and complex in terms of materials and resources applications. These products contain a plethora of materials, including metals, polymers, and ceramics, creating a new stream of complex waste products that have been difficult to recycle using current recycling technologies and has often been directed to landfills and incineration plants.

Electrical and electronic equipment are rich in precious metals (gold, silver, copper, platinum, and palladium), rare earth metals (neodymium, cerium, europium, lanthanum),[1] other metals (lithium, cobalt, and nickel),[2] and ceramics. Most of these metals are found in circuit boards, electrical components attached to the circuit boards, energy-storage, and energy-delivery units. In 2021, global electronic waste (e-waste) generation was 57.4 million tonnes.[3] This has led to issues with toxic elements leaching into the environment, along with the missed opportunity of "urban mining" to recover metals from e-waste. There is a similar scenario for solar panels, which are increasing exponentially as the global space seeks to meet net zero emission targets. In 2021, global solar-energy generation was greater than 1000 TWh and projected to grow by more than 25% annually until 2030.[4] Current solar panels are predominantly made of polycrystalline silicon, with more than 95% market share.[4]

Similarly, the transition from on-demand to availability-based power generation has increased the use of battery energy-storage systems (BESS), which involves installation of a home-scale or large-scale BESS. BESS are usually based on lithium-ion batteries (LIBs). In 2021, there were around 16 GW of grid-scale BESS globally. This figure was projected to reach around 680 GW by 2030, to stay on track to reach net zero emissions target, with an average addition of 80 GW per year.[5] Net zero emissions targets have been influencing the transport industry as well, with consumer-centric electric vehicles (EVs) introduced by major car manufacturers, including

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Tesla, General Motors, and Toyota. The global EV market reached 10 million electric cars in 2020, which was 4.6% of total car sales in that year.[6] EV batteries are constructed from the base materials of aluminum, iron, and copper. They also contain precious and expensive metals, including cobalt, manganese, lithium, nickel, and graphite.[7] The use of batteries has also increased in consumer electronics, with growing mobility of equipment. Increased adoption of EV automobiles and a continued rise in production of consumer electronics will generate large volumes of battery waste. This waste stream will be rich in precious and base metals, which are currently mined from primary natural ores.

The conventional "linear" supply chain currently used by the manufacturing and consumer economy synthesizes natural resources into consumable products and discards the products at their end of life as waste.[8] This linear process has proven to be untenable as the natural resources are declining. Therefore, closing the loop to attain a sustainable ecosystem for the supply chain (using the principles of the circular economy) is important. The circular economy helps to reduce dependency on natural resources, by making the economy self-sustaining using a cascaded loop system to reuse waste as secondary resources.

The major attributes of the circular economy are to nullify any form of waste and reduce the consequent pollution, instigate renewable material policies, and decouple the economy from finite natural resources. The adoption of a circular economy model will create a thriving sustainable economy that is designed to address ongoing global challenges, including climate change, waste management, loss of biodiversity, and pollution.[9]

Resources embedded in long-life electronics, energy-storage, and solar photovoltaics

Electronic waste

The amount of e-waste has been growing rapidly due to the rapid rate of innovation in the consumer electronics sector. Original equipment manufacturers (OEMs) are manufacturing new products every year and reducing the use life of the electronic products. This has resulted in an exponential increase in the volume of e-waste. The composition of waste from electrical and electronics equipment (WEEE) is generally divided into organic materials, ceramics, and metals. The organic materials are polymers, including polyethylene (PE), poly(vinyl chloride) (PVC), and phenolic resins (PF); and organic pollutants include brominated flame retardant (BFR), polybrominated biphenyl (PBB), and polybrominated diphenyl ether (PBDE); and glass fibers, including epoxy resin and tetrabromobisphenol A1 (TBBPA).[10–12] The embodied polymers are used for encasing and as a structural base material to replace the metals due to their light weight, water resistance, and ease of handling and manufacture, and account for around 21% of the total weight of the waste.[13] In addition to polymers, there are some organic pollutants, which are used for fire safety in electronics. As electronic equipment is shrinking in size, the amount of heat produced (and the associated risk) are controlled using flame-retardant coating (**Table I**).

Metals account for around 40% of e-waste by weight. These metals can be broadly classified into ferrous and nonferrous types and are mostly concentrated in printed circuit boards (PCBs). The predominant ferrous metals found in e-waste include iron, steel and nickel, and copper is the most found nonferrous metal. E-waste also contains trace amounts of precious metals, such as gold, silver, and platinum. However, the trend of using precious metals in electronics has been declining. Studies show that the amount of gold has decreased from 4 g in early computers, to around 1 g in the current generation of computers.[13] Hazardous metals such as mercury and lead are also found in e-waste, and recycling is necessary to prevent those metals leaching into the environment. Finally, there are a range of rare earth metals, including neodymium, cerium, and lanthanum, which are resource-intensive to extract from natural ores and their extraction can add value to the recycling process.

PCBs constitute around 3–6% of total electronics waste.[20] Annual e-waste generation in 2021 was 57.4 million tonnes[3] and considering 50% recycling rate for e-waste,[3] around 0.85–1.7 million tonnes of PCBs go to waste. The average e-waste composition data from **Table II** have been used to calculate the concentration of metals in e-waste streams (shown in **Table III**).

Energy-storage units

Broadly, there are four different kinds of batteries in use, classified by the base elements used in each. They are lead–acid batteries, nickel–cadmium batteries, nickel–metal hydride batteries, and LIBs.[22] In addition to the base metals that make up the electrodes, batteries also contain materials, including encasing, consisting of plastic and metal alloys; electrolytic medium, made up of soluble salts and acids; and polymers and ceramics in solid-state batteries.[23] Currently, LIBs are gradually replacing other types of batteries, due to their portability and high energy to weight ratio. The use of LIBs has further been helped by the restriction in use of cadmium by the European Environment Agency Council Directives 91/157/CEE and 91/138/CEE due to its associated health hazards.[24] Also, lead–acid batteries have a lower energy density than LIBs and contain highly corrosive sulfuric acid, which makes them unsuitable for portable equipment and devices.[25] Lead–acid batteries are still currently used as auxiliary power sources in EVs. They are also used to power the ignition of internal-combustion engines in the majority of passenger vehicles, which accounts for 85% of global lead consumption (**Table IV**).[26]

The recycling rates for lead–acid and nickel–cadmium batteries are very high, at 75–85 percent.[27] LIBs have a much lower recycling rate of around 5%,[28] with more than 544,000 tonnes of LIB waste disposed in landfills.[29] Researchers have projected that this will increase to more than 2 million tonnes by 2030, due to growing digitization (production and disposal of consumer electronics) and uptake of EVs and BESS.[30] The monetary value of materials contained in LIB waste is shown in **Table V**, with prices of metals taken from Reference 31.

Solar panels

Solar cells are predominantly composed of silicon, in monocrystalline and polycrystalline form. Although these forms of silicon are the energy-absorbing units in photovoltaic (PV) solar panels, they constitute only around 4% of each module's total weight percentage. The most common materials used in PV modules are glass (as a cover window) and aluminum (used as an encapsulation frame for the panel).[41] Silicon-based solar cells comprise 90% of the total market, with gallium arsenide (GaAs) and organometallics (such as soluble platinum) constituting the rest of the market.[42] GaAS solar cells have limited scope, due to the hazardous nature of arsenic and the scarcity of gallium.[42] Likewise, the use of organometallic-based solar cells is still under development, although they have better bandgaps compared to silicon and are also more lightweight and cheaper to manufacture.[42]

The joint study done by the International Renewable Energy Agency (IRENA) and the International Energy Agency Photovoltaic Power Systems (IEA-PVPS) has forecast that by 2050, 5.5–6 million tonnes of PV waste will be generated, which translates to USD $15 billion.[43] The material composition of silicon-based solar panels is provided in **Figure 1**. Thin-film solar panels, which are used for low-power applications, contain elements, including amorphous silicon, cadmium telluride, and copper iridium gallium selenide (CIGS).[44] Emerging solar panel technologies, such as concentrator PV, dye-sensitized solar panels, and organic solar panels, contain materials, including titanium, platinum, and organic polymers.

Methods and challenges for current recycling processes

E-waste

The recycling process for e-waste can be broadly divided into thermal (pyrometallurgical) and non-thermal (electro/hydrometallurgical) processes. E-waste needs to be pretreated using processes, such as milling, mechanical separation, dismantling, and pyrolysis.[15] The characteristics and drawbacks of thermal and non-thermal recycling processes are shown in **Table VI**.[15] Pre-processing steps are required to decrease the energy consumption of the recycling process and increase the concentration of metals by separating metallic and nonmetallic components. Mechanical separation is generally used for pre-processing as it does not involve any chemical changes and does not generate toxic effluents.[45]

Several industrial-level thermal and non-thermal recycling processes are used to recycle and extract metals from e-waste. Commonly found metals, including copper, iron, and tin are suited for thermal recycling processes. Metals found in smaller proportions—including precious metals (Au and Ag), and rare earth elements (REEs) such as Ry,

Table I. General composition of e-waste.[10–12,14]

General Composition	Type of Compounds	Type of Elements and Polymers	Remarks
Organic materials (30%)	Polymers	PE, PVC, PTE, PF, SAN, and nylon	Recyclable
	Organic pollutants	BFR, PBB, PBDE	
	Glass fibers	TBBPA, epoxy resins	Nonrecyclable
Ceramics (30%)		Silica, aluminum, and earth oxides	
Metals (40%)	Ferrous metals	Iron, nickel	Hazardous metals (Hg, Zn, Pb, Be)
	Nonferrous metals	Copper, aluminum, mercury, lead, zinc, tin, cadmium, gold	Precious metals (Au, Ag, Pt, Pd)
			Rare earth metals (Ta and Ga)

Table II. Concentration of metal in e-waste and ores.[15,16]

Element	From e-waste[17]	From e-waste[18]	From e-waste[19]	E-waste Average	From Ores
Copper (wt%)	20	14.6	19.56	18	0.5–3.0
Iron (wt%)	8	4.79	11.47	8	30–60
Tin (wt%)	4	5.62	3.68	4.5	0.2–0.85
Lead (wt%)	2	2.96	3.93	3	0.3–7.5
Nickel (wt%)	2	1.65	0.38	1.35	0.7–2.0
Gold (ppm and %)	0.1	0.02	0.03	0.05	0.0005
Silver (ppm and %)	0.2	0.045	0.05	0.098	0.0006

Rh, Pt, and Pd are more suited for hydrometallurgical, electrometallurgical, and pyrometallurgical recycling processes, due to the extraction efficiency of these techniques (**Table VII**).[46]

There are several challenges to overcome to increase the proportion of e-waste that is recycled. The material composition of e-waste is complex and includes layers of polymers, fibers, and metals. This makes it difficult to achieve efficient recovery of metals using a single-treatment procedure. For example, in Umicore's precious metal refining process, PCBs are shredded in two stages into 7-mm fragments and then processed using a smelter to extract the metallic content of the waste. The metallic content is then processed using selective multistage leaching to extract various metals over multiple stages.[47] The complexity of the treatment process is proportionate to the economic viability of installing the recycling plants, making complex processes less accessible to the full range of consumer demographics. Another major challenge is the collection, sorting, and inhomogeneity of e-waste. E-waste is generally mixed and treated with municipal waste, and there are a lack of separate e-waste collection centers. Another hurdle is the varying material composition of e-waste, which results in non uniform extraction output (**Table VIII**).

Energy-storage units

Long-life energy-storage units basically contain LIBs. Generally, spent LIBs are recycled using physical and chemical processes, due to the complex layering of materials in the LIB and the variation in the type of metals used in electrodes. The spent LIBs contain residual energy, which can lead to fire and explosions during recycling,[55] so batteries need to be discharged before recycling. Following discharge, the principles of recycling spent batteries are similar to e-waste, with a pretreatment process followed by a metallurgical process,

Table III. Monetary value embedded in e-waste in 2022.

Element	E-waste Average (wt%)	Weight (million tonnes)	Price per Tonne (USD)[21]	Total Value in Trillions (USD)
Copper	18	0.153–0.306	7421	1.135–2.27
Iron	8	0.068–0.136	99	0.06–0.013
Tin	4.5	0.038–0.076	20,874	0.8–1.6
Lead	3	0.025–0.05	1753	0.045–0.09
Nickel	1.35	0.0114–0.0229	21,881	0.25–0.5
Gold	0.05	0.000425–0.00085	53 million	22.1–44.2
Silver	0.098	0.0008–0.0016	550,000	0.49–0.98

Table IV. Composition of different types of battery.

Type of Secondary Battery	Components			Common Metals	References
	Cathode	Anode	Electrolyte		
Lead–acid	Lead oxide (PBO_2)	Lead	H_2SO_4	Pb	32
Lithium ion	Lithium nickel, manganese cobalt, $LiFePO_4$ and $LiCoO_2$	Graphite	$LiClO_4$, $LiBF_4$, $LiPF_6$	Li, Ni, Co, Cu, Al, Fe	33,34
Nickel-based (NiCd/NiMH)	Nickel hydroxide	Cadmium, iron, or metal hydride	KOH, NaOH, and LiOH		35

Table V. Composition and value embedded in lithium-ion battery.

Metals	From LIB (wt%)[36]	From LIB (wt%)[37]	From LIB (wt%)[38]	From LIB (wt%)[39]	From LIB (wt%)[40]	Average (wt%)	Average (tonnes)	Total Value in Millions (USD)
Cobalt	15.51	16	16.5	29.49	22.31	20	108,800	566
Lithium	2.27	2	2	3.14	2.74	2.43	13,220	687
Copper	9.54	10	7.1	16.48	7.47	10.12	55,052	408
Aluminum	3.43	3	4.1	8.02	9.78	5.67	30,845	70
Iron	19.31	19	–	–	–	19.16	104,230	10.30
Nickel	–	–	–	0.02	0.40	0.21	11,424	250

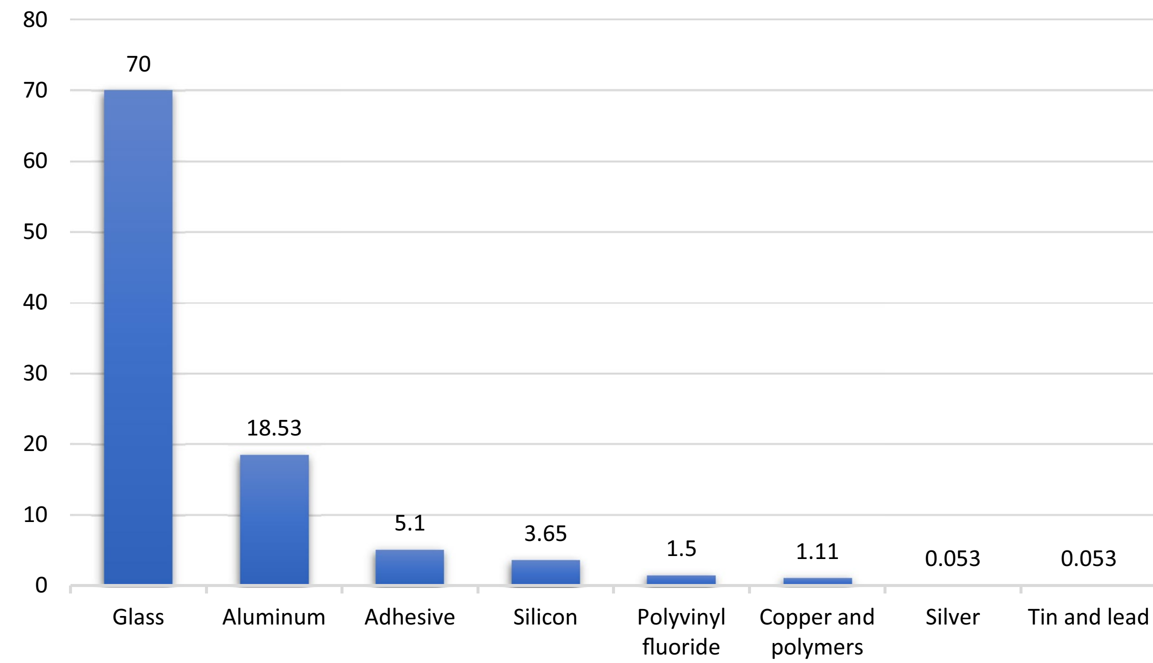

Figure 1. Weight percent of components of photovoltaic module.[41]

including pyrometallurgy, hydrometallurgy, and electrochemical processes.[56] Pretreatment is carried out to increase the metal composition density and make the metallurgical processes more efficient (**Tables IX, X**).

There are several tradeoffs when considering the effectiveness and impacts of different treatment methods. Pyrometallurgical processes are energy-intensive due to the use of smelters and furnaces, and the heat treatment of the LIBs can produce hazardous gases (furans and dioxins). Similarly, material losses are also common. In the same way, the hydrometallurgical process uses leachate (acid and bio-leachate) and recovery agents for solvent extraction and electrochemical deposition, which results in a high recovery rate (>95%) but involves the risk of waste effluents, and the direct physical recycling process is a simple, low energy, and less resource-intensive method, but the recycled and reused material cannot match the long-term performance of virgin materials.[56] This demonstrates that all available recycling methods have their inherent sets of advantages and disadvantages, which should be considered when selecting an appropriate technique.

Changes in battery composition can also drive the need for development of new recycling techniques. For example, in the past, cobalt has been the most common and expensive metal in LIBs, and it has been extracted using pyrometallurgical techniques at a commercial scale. However, the use of cobalt in new LIBs has been gradually decreasing, and nickel and manganese have been increasing. This has created a need to develop new recycling techniques for the new focus materials.

Table VI. Comparison of thermal and non-thermal processes.[15]

Types	Thermal Process	Non-thermal Process
Characteristics	• Used for metallic materials, by thermal decomposition of non-thermal components • Requires technology to control hazardous fumes • Economically viable for recycling high-grade materials only	• Pretreatment process (e.g., mechanical milling) required • Use of chemicals and reactants to leach precious metals • Investment for treating waste • Liquid discharge required
Impacts	• Hazardous fumes, dioxins, and benzofurans produced during thermal treatment	• Discharge of toxic wastewater • Use of high pH acids and reactants

Solar panels

Solar panels are manufactured with an average lifespan of 30 years, and these robust designs are created by complex layering and incorporation of different kinds of materials.[63] This makes material recovery a major challenge. Most of the recycling techniques available for solar panels are limited to the laboratory and pilot scale,[63] with very few opportunities for commercial-scale recycling. Almost all of the commercial-scale recycling technology is based on direct physical separation, where the separation of components, including the aluminum frame, junction box, wires, and silicon-glass wafers is completed. An integrated recycling approach for solar panels includes three key steps: mechanical separation of the aluminum frame and junction box; separation of encapsulation through thermal or chemical processes to

Table VII. Industrial-scale e-waste recycling.

Industrial Process	Recovered Materials	Attributes	References
Umicore's Process	Diamagnetic (Au, Pb, Ag, Cu), precious metals (Pd and Pt), REE (Ru and Rh), Paramagnetic (Ni, Co)	Hybrid techniques with thermal treatment using blast furnace, smelter, and hydrometallurgical leaching process	47
Müller-Guttenbrunn Group (MGG)	Separation of ferrous and nonferrous materials after collection, depollution, and shredding process	Capacity of 80,000 tonnes of e-waste per year. Can produce metal-rich ores, which need to be further treated to extract metals in pure form	48
NEC Group	Separation of Cu-rich powder and glass fibers and resins	Copper separated from glass fiber and resin powder	46

Table VIII. Different types of e-waste recycling techniques.

Process	Subtype	Properties	References
Pyrometallurgy	Smelting	Copper and precious metals can be recovered with a 95% recovery rate	49
	Alkali smelting	Dioxins and furans can be avoided by heat-treating at 400°C and plastics and ceramics can be separated	50
	Metal trapping method	Precious metals can be recovered by trapping Cu and Fe and have a higher recovery rate	51
	Matte collecting method	Can be operated for low melting points with good liquidity of materials	50
	Plasma melting technology	High energy consumption (>2000°C) and high recovery rate with minimum waste gas and water generation	52
Hydrometallurgy	Chlorination leaching	Chloride emissions cause pollution but can be operated in low investment	50
	Iodination leaching	High recovery rate but has high cost	50
	Cyanide leaching	High recovery rate and low energy consumption but cyanide is hazardous	50
	Halide leaching	High recovery rate with less energy consumption but halide is highly corrosive and has oxidizing properties	50
	Supercritical fluids extraction	High recovery rate for precious metals like Pt and Pd and REE (Rh) but requires preprocessing using mechanical treatment, which causes a 20% loss of metal content and produces waste oil and gas	50
	Liquid–liquid and solid-phase reaction	Selective metal extraction can be carried out with high extraction efficiency, but the processes are volatile and toxic	53
	Microwave-assisted leaching	Microwave-assisted heating can reduce the reaction time and induce a high recovery rate, but it is still in the early stages of development	50
Electrochemical	Electrochemical decomposition process	High energy efficiency, minimal chemical usage, and low environmental impact, but is cost inefficient	54

separate glass and silicon substrate; and finally, use of further purification processes using electrical and chemical treatments to recover metals such as silver, copper, tin, and lead from the waste.[63]

Current solar panel recycling techniques are based on extracting specific elements from the solar panel and thus are not suited for complete recycling of the panels. The upscaling of pilot plants to commercial scale is further hindered by the complex nature of techno-economic analysis and life-cycle assessment of the complete recycling process. This includes the complicated material and energy flow for the raw materials used to manufacture the PV modules. For instance, although the selective recycling approach provides a high recovery rate for specific elements, it can be ineffective for large-scale adoption due to the complex material and energy flow system of the logistic and manufacturing systems.

There are a very limited number of integrated recycling technologies currently in development for solar PV modules. One example is the full recovery end-of-life PV (FRELP) technique. This technology is based on a sequence of mechanical and thermochemical processes that recycle waste crystalline silicon PV panels into glass, aluminum, silicon, copper, and silver—with a recovery rate of more than 95 percent.[64] The mechanical treatment includes disassembly of the panel to separate aluminum encasing, junction box, and cables. Then, a controlled thermal treatment is used to separate the silicon-glass multilayer, which inhibits the gluing effect of EVA. This

Table IX. Components of LIBs.[56]

Component	Composition
Cathode	$LiMO_2$, $LiFePO_4$ (M = Co, Ni, Mn)
Anode	Copper or graphite
Electrolyte	$LiPF_6$ and organic solvent (ethylene carbonate, ethylmethyl carbonate, diethyl carbonate, etc.)
Separator	PE/PP
Case	Al-polymer layer, stainless steel

Table X. Methods and results for battery recycling pretreatment and treatment methods.

Process	Methods	Results	References
Pretreatment	Crushing and sieving process followed by hydrometallurgical process	Extracting cobalt and lithium	57
	Thermal pretreatment followed by shredding to peel off and collect $LiCoO_2$		58
	Crushing and ultrasonic washing	12-mm screen aperture for crusher and 15-min ultrasonic washing has high recovery rate	37
Pyrometallurgical	Dismantled battery cells fed to shaft furnaces with three heating zones, designed by Umicore	Electrolyte vapor releases in preheating zone, plastic pyrolysis in pyrolyzing zone, and alloy (Co, Ni, and Fe) and slag (Li, Al, Si, and Fe) formed in smelting zone	59
	High-temperature heat treatment using electric arc furnace followed by hydrometallurgical steps, developed by Georgi-Maschler	Co alloy and Li concentrates are formed	60
Hydrometallurgical	Acid leaching using inorganic leaching agents (HCl, HNO_3, H_3PO_4), organic leaching agents (citric acid and oxalate acid)	High recovery rate of the metals, but treatment time is long, and the output is dependent on temperature, acid concentration, and additives	37,61,62
Electrochemical decomposition	Leached solution can be processed through ECD to selectively separate metals	Pure metals or metal hydrides can be extracted with high energy consumption	56
Direct physical recycling	Recover components from the spent LIBs directly without any chemical treatment under the influence of supercritical CO_2	The recovered cathode materials and electrolytes can be directly reused with relithiation	56

heat treatment can be carried out efficiently with an infrared system. The separated layers are then treated separately, with glass undergoing optical treatment and refinement, while the silicon layer is further incinerated to detach the back sheet layer. Next, the shredded silicon layers are treated with acid leaching and electrolysis techniques to recover silver (94%), copper (97%), aluminum (99.4%), silicon (97%), and glass cullet (98%), with purity of N/A, 99%, 99.99%, scrap grade, metallurgical grade, and 98%, respectively.[64,65]

The general recycling flow for all e-waste, batteries, and solar panels is similar—with direct physical separation followed by a series of pyro-, hydro-, and electrometallurgical techniques. These steps are complicated and need to be customized to each kind of waste. For solar panels, the general structure of the product is similar across PV modules of all sizes. For waste PCBs and LIBs, the size and composition vary based on the application area. This creates an inhomogeneous stream of waste that affects the treatment procedure, recovery rate, and purity of recovered elements. As previously mentioned, the gradual decrease of cobalt in lithium cathodes and its replacement with metals, including nickel and manganese,[56] have affected the efficiency of existing recycling plants. These kinds of alterations in the composition are common across the electrical and electronics ecosphere, thus a continuous R&D effort to implement new forms of materials and increase the techno-economic effectiveness of the product is required. This means that recycling technology also needs to continuously evolve to adapt efficiently to product changes. This transition can affect the economic benefit of the material recovery from the large-scale plants.

Another barrier facing recycling processes is sorting and collecting the waste from consumers. Unlike the robust and efficient logistical supply chain system that distributes products from manufacturers to users, the loop-back supply chain which collects end-of-life products is still at a rudimentary stage, with only a few countries (such as Japan and Germany) trying to create a sustainable infrastructure for material recovery and a recycling supply chain.[66]

Applying circular economy principles to long-life-cycle products

The current recycling system for long-life-cycle products represents an inverted material flow with respect to the current supply chain system. End-of-life products are collected via collection centers and then transported to centralized large-scale facilities where they are recycled. In some cases, there are also some pre-processing steps in decentralized processing facilities. For example, the encasing of e-waste may be taken apart, the aluminum frames of solar panels are separated, or the spent LIBs are completely discharged. Nevertheless, most recycling treatments are carried out in centralized facilities. This direct material flow inversion has put intensive pressure on the already ailing logistical and supply chain system, which impacts the process for recycling plants, thereby affecting how well the loop can be closed for circularity. These shortcomings can be addressed by introducing measures such as those discussed in the following sections.

Extended product responsibility

Extended product responsibility (EPR) requires the product manufacturer to take extra financial and physical responsibility to treat or dispose the post-consumer product.[67] The National Television and Computer Recycling Scheme for recycling of old computers and television, which is an industry funded scheme, and supported by the Australian government, comes under product stewardship programs rather than EPR. So, a clear EPR policy is required to facilitate the producer and manufacturer to implement EPR in Australia. A product manufacturer already has a set material flow system used to deliver finished products to the consumer, and the same chain can be used to redirect end-of-life products to recycling facilities. This will allow for efficient collection and sorting of end-of-life products. For example, current WEEE directives classify WEEE in 11 general classes. These classes include large- and small-scale household appliances, consumer electronics, lighting equipment, and electrical and electronic tools.[68] These general classification types lead to further resource utilization in sorting and separating the waste, and even that will be a heterogeneous mixture of products. For these reasons, an extended manufacturer EPR is a more effective and sustainable way to close the loop.[67]

Developing recycling infrastructure and material flow system

There are several steps to be addressed before a circular recovery system for long-life-cycle products is established. As discussed in the previous section, most of the recycling techniques used for material extraction of long-life-cycle products are focused on a narrow spectrum of materials, which makes upscaling for large-scale adoption economically unviable. An integrated recycling approach that allows full recovery of component materials needs to be developed and incorporated into the material flow system.

There are already millions of tonnes of end-of-life products generated each year, which manufacturers do not take responsibility for recovering. These products still need to be handled using conventional distribution and collection systems. The current solid waste collection and sorting facilities at the municipal level are more suited to short-term products, such as plastic and domestic waste. Existing collection bins, transportation facilities, and sorting facilities cannot accommodate the products, such as large-scale batteries, WEEE, and solar panels. This results in a very limited recycling rate of 50% and 5% for WEEE and LIBs, respectively.[3,28] The limited amount of end-of-life product collection can be bolstered by increasing the number of collection points provided by manufacturers and Councils. Manufacturers can set up collection points in their retail centers, while large household appliances could be collected from consumer homes on replacement.

An innovative form of decentralized recycling system could also be developed to complement the existing centralized system. This decentralized system could take up the small-scale material flow and use specific recycling techniques to ensure efficient material recovery from the waste. Using similar principles of distributed recycling, the MICROfactorie concept (discussed in the following section) can further assist in closing the material flow loop for a sustainable circular economy.

MICROfactorie: Distributed recycling

MICROfactorie uses the concept of microrecycling where waste material can be treated on a small scale, so that it can be implemented into a distributed and decentralized system, in a modular basis, which can be applied in a society level that adapts to the type of waste generated by the area. This overcomes the limitations of the conventional recycling system, by bypassing the need to have collection centers and transportation infrastructure to transfer the waste material to recycling plants. The benefit of having microrecycling plants is that they can be adaptive to ever-evolving product design and material composition and can be implemented easily, with fewer resources and less economic pressure. The development of distributed recycling will also support the distributed manufacturing concept, which has gained traction with the introduction of additive manufacturing. Distributed manufacturing fed by a distributed supply chain providing materials extracted from recycling will help create a sustainable economic ecosystem, where the material flow loop can be closed in an effective manner.

Selective thermal transformation techniques implemented by the researchers from the Centre for Sustainable Materials Research and Technology have shown that complex waste streams (including e-waste) can be recycled by extracting copper- and tin-based alloys at different stages of thermal transformation.[14,69] Similarly, extraction of nickel-based alloys from NiMH batteries,[70] as well as cobalt and lithium from LIBs,[71] has also been accomplished using microrecycling techniques. Likewise, other microrecycling techniques, such as oxidation–reduction processes to extract REEs from e-waste, with a recovery rate of 90–100%,[72] have also been verified.

Sustainable design

The product can be designed to be easily recyclable, making the material recovery process less resource-intensive, by incorporating sustainable design, proper material selection, and manufacturing and fabrication techniques. It can be done by adhering to the concept of EPR by the manufacturers with the development of different material fabrication techniques for effective recyclability. The evolving material selection in e-waste has shown reduction in use of REE, precious metals, and toxic elements with increasing use of base metals, such as copper, iron, and silicon. Similarly, there has been a reduction in use of brominated organic compounds in electronic equipment, which has simplified the recycling process of the e-waste. Likewise, in batteries, the use of toxic metals such as cadmium has been restricted[73] and the types of energy-storage devices available are being streamlined into types, such as lithium, lead, and nickel-based. Similarly, for PV panels, the types of material used have been predominantly silicon, aluminum, and glass. This simplification in the material choice and design concepts helps in developing an effective recycling technique and this trend can be adopted across all product classes.

The material extraction and recycling process of the long-life waste can be further solidified by adopting modular designs to facilitate product reusability to help extend the lifetime of the product. There has been an effort to make consumer products such as handheld devices modular under right to repair laws,[74] which allow the consumer to replace only the defective part of the equipment, rather than the whole device. This effectively reduces the amount of waste generated and keeps the material in the usable phase for a longer time in the circularity. Similarly, for PV panels, there has been an approach for making ease-to-disassembly design improvement to make the dismantling and recycling process convenient, and there has been a transition from wafer-based PV design to thin-layer design, which requires less semiconductor material and has more efficiency.[75]

Advances in recycling techniques

Current recycling techniques are material-selective and can be used only for specific groups of metals to be extracted from the waste. As discussed in a previous section, the recycling techniques used for e-waste can only extract specific alloys, such as copper or tin or precious metals, while the rest of the materials such as polymers are discarded as byproduct. An integrated approach that recycles the e-waste, where all the materials can be extracted efficiently, needs to be developed. The approach of MICROfactorie can help in an integrated approach, but advancement and focus on large-scale adoption of this technology are required with development in effective recycling techniques for different kinds of products.

Most of the recycling approach for waste LIBs are based on a conventional metallurgical (hydro, pyro, and electro) approach, which is highly energy-intensive and produces byproducts in the form of toxic fumes and liquids and electrolyte discharge. These factors can affect the benefits of material extraction and innovation in new recycling techniques is required. Likewise, recycling of solar panels needs a large amount of pretreatment involving manual handling for dismantling of the solar panel to manually sort the frames, glass, and the panels. It can be highly resource-intensive and ineffective when large-scale processing needs to be done.

Summary of shaping a circular economy for long-life-cycle products

The immediate and long-term effects of disposing of long-life-cycle products, including LIBs and solar panels cannot be comprehended in full at this stage, because most products are still in circulation. However, after the life cycle of 30 years for solar panels and around 10 years for EV batteries, the impact of this kind of waste will have devastating effects on the environment. These effects can range from leaching in soil and water to percolation into the food ecosystem. These effects can be extrapolated from the e-waste situation, which is a well-researched and quantified domain, where effects, including heavy metal leaching into the environment lead poisoning in humans and effects on aquatic life have been documented in the literature.[76–79]

The amount of base metals, precious metals, and rare earth metals are on par with or greater than the natural ores available.[80] And, considering the recycling rate of e-waste (50%) and LIBs (5%), most of these metals are lost to landfills. This trend has created an unsustainable linear economy, adding more stress to limited natural resources, which can be converted to a more sustainable circular material flow model, using end-of-life products as a secondary source of metal. The waste products can be recycled using a more integrated recycling approach to achieve an efficient recovery rate of value-added elements in the waste, which then can be circulated back to the material flow system. Similarly, by implementing EPR and stewardship policies, waste products can be treated effectively, and manufacturers can implement sustainable design to facilitate ease of recovery from the waste materials. To attain a more effective model of circularity, there needs to be an innovative form of recycling, reducing the stress from the ailing centralized material flow system, by introducing a more decentralized and economy-of-purpose model of microrecycling. This can help treat the disposed waste at a consumer level, which can have a higher recovery rate.

The inverse material flow model to attain circularity will put more stress to the existing supply chain system, so upscaling in collection, sorting, and transportation infrastructure needs to be done. The recycling facilities also need to innovate their technologies to effectively recover material from the evolving material design products. Thus, a coherent ecosystem with a centralized recycling system complemented by decentralized small-scale recycling can help get us a sustainable circular flow model for the long-life products.

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