United States Energy Association: Critical Material Recovery from E-waste

Final Report

Subagreement No. 633-2023-004-01

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August 30, 2023

Disclaimer

Executive Summary

This report was developed for the United States Energy Association (USEA) to describe the opportunity for recovering critical materials (CMs) from electronic waste (e-waste). The research summarized herein includes: 1) a review of the location and purpose of CMs in a selection of electronic devices, 2) descriptions of the current supply chain, recycling infrastructure and the challenges they pose in achieving e-waste circularity, and 3) an assessment of state-of-the art recovery technologies, their current scales, and the existing gaps. This report covers a subset of CMs that are most relevant to e-waste. This list includes aluminum, arsenic, gallium, indium, nickel, tantalum, tungsten, titanium, tin, platinum group metals (PGMs - platinum, palladium, rhodium, ruthenium, osmium, and iridium), and rare earth elements (REEs - lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium, and yttrium).

The review indicates that CMs are found in a range of concentrations in the major categories of e-waste covered in this report, which are wind turbines, solar panels, phones, computers, screens (cathode-ray tube [CRT], light-emitting diode [LED], or liquid-crystal display [LCD]), electric vehicle magnets, and medical devices. CMs are often in the form of magnets, semiconductors, and phosphors, but they can also be used for structural and electrical applications.

Overall, there is a lack of directly scaled and/or applicable technology for recovering CMs from e-waste. Promising laboratory-scale technologies should be studied at larger scales to validate them for industrial use. Existing industrial-scale recovery efforts should be expanded to secure future supplies. Additionally, there is a need to fund more research both in 1) technologies to recover CMs from specific components, such as transparent screens, with high concentrations of high-value materials, and 2) technologies / strategies for comprehensively recycling products that contain multiple valuable materials.

However, bridging gaps in CM recovery technologies alone is not sufficient to achieve circularity. A variety of strategies should be integrated with technological innovations to drive recovery efforts such as: better regulations, policy changes, connections between supply chain segments, end-of-life management, incentive structures around collection and recycling, incentives around better product design while incorporating R10 circular strategies, and stakeholder behavior changes.

In summary, this report illustrates that there is both a significant opportunity and a need for recovering CMs from e-waste through technological innovations and supply chain/recycling infrastructure improvements. CMs are vital for many modern technologies and defense applications, especially those related to clean energy. Recycling e-waste is a crucial strategy to enable a domestic market supply chain capable of producing a long-term supply of these elements.

Table of Contents

List of Figures

Page

List of Tables

1.0 Critical Materials in Electronics

1.1. Introduction

Consumer electronics, green energy, and defense capabilities rely largely on using critical materials (CMs). CMs are vital to the US economy and national security, as they are the essential building blocks for many modern technologies, especially those related to clean energy and defense. Rare earth elements (REE), platinum group metals (PGMs), and critical metals such as cobalt, nickel, and arsenic are universally employed in the electronics necessary for day-to-day life. While these elements are not rare in the Earth's crust, they are often geopolitically constrained, as well as difficult and expensive to mine. Oftentimes, mine sites are located near tribal lands or endangered species, which add additional environmental constraints. There are also cultural, societal, and environmental justice aspects to consider in projects that involve the mining industry. As a result, the market is primarily dominated by foreign suppliers who control the world supply of these metals. The world's demand for CMs is anticipated to increase by 400 to 600 percent in the coming decades (The White House 2022). Recycling is a crucial strategy to enable a domestic market capable of producing a long-term supply of these elements.

This report describes the opportunity for recovering CMs from electronic waste (e-waste).

- Chapter 1 provides salient market and import reliance information for the following CMs – aluminum, arsenic, cobalt, gallium, indium, nickel, niobium, tantalum, tin, titanium, tungsten, zinc, PGMs (iridium, palladium, platinum, ruthenium), and REEs (cerium, dysprosium, europium, gadolinium, lanthanum, neodymium, praseodymium, samarium, terbium, and yttrium). The chapter describes the typical concentrations of CMs in various categories of e-waste and the purpose of the CMs in electronic devices.
- Chapter 2 presents the benefits of recycling and circularity while promoting sustainable economic development in the e-waste supply chain.
- Chapter 3 provides a general description of the most common technologies used for metal recovery – such as pyrometallurgy, hydrometallurgy, biometallurgy, etc.
- Chapter 4 examines the current state of CM recovery from e-waste for a refined list of 32 CMs. The selected CMs were based on a variety of factors such as availability, market demand and price, import reliance, and typical concentration in electronic devices.
- Chapter 5 describes the gaps in technology and infrastructure related to CM recovery from e-waste.
- Chapter 6 provides a summary and recommendations for CM recovery from e-waste based on results of research for this report.

To gain insight into the CM need, salient market statistics and import reliance were considered. This data is provided in Table 1-1. Table 1-2 documents the concentrations of CMs in various electronics. The location and purpose of CMs in electronics were carefully considered to better understand potential recycling opportunities. Table 1-2 only reports information for CMs that were confirmed to exist in at least one of the major categories of e-waste covered in this report, which are wind turbines, solar panels, phones, computers, screens (cathode-ray tube [CRT], light-emitting diode [LED], or liquid-crystal display [LCD]), electric vehicle magnets, and medical devices. Because recycling and CM recovery from batteries are already reasonably understood, batteries were excluded from this report. Lithium, a CM whose leading global use is in lithium-ion batteries (US Geological Survey 2023), was not included in the initial list of CMs for this reason.

Table 1-1: Salient market and recycling information for CMs [Information adapted from (US Geological Survey 2023)].

Critical Material	2022 Market Price ($/kg)	Import Reliance (%)	Current Recycling Information (2022)
Aluminum	3	54	Amount recycled from old scrap equaled approximately 29% of apparent consumption. A $2.5 billion aluminum recycling plant is currently under construction in Alabama and is to be completed by 2025.
Arsenic	4	100	Very limited amount of recycling of GaAs semiconductor new scrap.
Cobalt	68	76	Amount in purchased scrap equaled approx. 24% of estimated cobalt consumption.
Gallium	420-640	100	No recycling of old scrap. One facility in New York reprocesses new scrap from gallium arsenide semiconductor manufacturing to obtain gallium of high purity.
Indium	250	100	Mainly recovered from indium tin oxide scrap in Japan and Korea. Some scrap containing indium is recycled in the US, but quantitative data is unavailable.
Nickel	24	56	Alloyed nickel can be recovered from nickel-containing waste. Recycled nickel accounts for 56% of apparent consumption. In 2022, $600 million was dedicated to projects to recover nickel from spent batteries.
Niobium	24	100	Recycled with steels and superalloys that contain niobium, but scrap recovery is negligible. Amount recycled may be up to 20% of apparent consumption.
Tantalum	150	100	Most recycling is of new scrap produced during the manufacturing of electronic components, cemented carbide, and superalloy scrap. Amount recycled may be up to 30% of primary processor consumption in the US.
Tin	35	77	Approx. 18,000 tons of tin from scrap recycled.
Titanium	11	>95	Not available
Tungsten	0.3	>50	Not available
Zinc	4	76	Approx. 60% of refined zinc produced domestically was recycled from secondary materials, such as galvanizing residues.
Platinum Group Metals			
Iridium	151,109	Not available	Not available
Palladium	70,732	26	Roughly 110,000 kg recovered globally from both old and new scrap. This figure includes 40,000 and 11,000 kg of Pd and Pt, respectively, from catalytic converters in the US.
Platinum	31,508	66	
Ruthenium	19,290	Not available	Not available
Rare Earth Elements + Yttrium			
Cerium	1	>95	Small amounts of REEs are recovered from various forms of e-waste, such as fluorescent lamps, batteries, and permanent magnets.
Dysprosium	390		
Europium	30		
Gadolinium	NA		
Lanthanum	1		
Neodymium	130		
Praseodymium	NA		
Samarium	NA		
Terbium	2,000		
Yttrium	13-43	100	An insignificant amount of recycling is occurring.

Table 1-2: Typical concentrations of critical materials in various categories of e-waste.

	Type of Electronic Device									
Critical Material	**Wind Turbines**	**Solar Panels**	**CRT-type Screens**	**LED/LCD Screens (Monitors and Notebooks)**	**LED/LCD Screens (Televisions and Other)**	**Cell Phones**	**Electric Vehicle Magnets**	**Computers**	**Medical Devices**	**References**
	* = NdFeB magnets ^ = steel alloys		* = TV ^ = monitor	^ = monitor & = notebook @ = PCB	* = TV $ = general @ = PCB			@ = PCB * = capacitor ^ = hard drive	* = MRI magnet ^ = implantable device @ = other	
Aluminum	0.8-2 %	7-17.5 % 1370 g	67 g* 14.1723 %^			3.1495 % 2.9-12 g			Varies@	(Buechler et al. 2020; Cucchiella et al. 2015; H. Cui et al. 2022; Demir and Taşkın 2013; Mone et al. 2017; Sica et al. 2018; Singh, Li, and Zeng 2016; Weckend, Wade, and Heath 2016; Wilburn 2011; Buechel et al. 2015)
Arsenic			0.0013 %^			0.004384 %				(Buechler et al. 2020; Singh, Li, and Zeng 2016)
Cobalt	2.99 %*		0.0157 %^			0.014-2.172 % 3.8-6.3 g	1.5%	0.02 %		(Buechler et al. 2020; Cucchiella et al. 2015; Ioannis Bakas and Baxter 2016; Singh, Li, and Zeng 2016; Venkatesan et al. 2018; BJMT 2023)
Gallium		0.119 g 0.01 %		3.3 mg^ 1.6 mg&	4.9-5 mg* 0.00006 %*	0.003546 %				(Buchert et al. 2012; Buechler et al. 2020; Cucchiella et al. 2015; Ioannis Bakas and Baxter 2016; Sica et al. 2018)

Table 1-2 (continued): Typical concentrations of critical minerals in various categories of e-waste.

Type of Electronic Device										
Critical Material	**Wind Turbines**	**Solar Panels**	**CRT-type Screens**	**LED/LCD Screens (Monitors and Notebooks)**	**LED/LCD Screens (Televisions and Other)**	**Cell Phones**	**Electric Vehicle Magnets**	**Computers**	**Medical Devices**	**References**
Indium		0.119 g 0.01 %	0.0016 %^	2.9 mg^ 1.5 mg[&]	3-4.4 mg* 0.00132 %[$]					(Buchert et al. 2012; Cucchiella et al. 2015; Ioannis Bakas and Baxter 2016; Sica et al. 2018; Singh, Li, and Zeng 2016)
Nickel	0.04 %* ≤2 %^ 240-403 kg/MW		0.8503 %^			0.0432-13.49 % 1-1.5 g		2 %[@]		(Coates 2021; Cucchiella et al. 2015; Diaz et al. 2016; International Energy Agency (IEA) 2021; Nnorom and Osibanjo 2009; Singh, Li, and Zeng 2016; Venkatesan et al. 2018; Sodhi and Reimer 2001)
Niobium	0.06 %*		0.0002 %^					Varies*	47 %*	(Singh, Li, and Zeng 2016; Venkatesan et al. 2018; Gorewoda et al. 2020; Montero, Guevara, and dela Torre 2012; Tantalum-Niobium International Study Center (TIC) 2017)
Tantalum			0.0157 %^					30 %[@,*]	30 %[@]	(Singh, Li, and Zeng 2016; Riedewald et al. 2023; Tantalum-Niobium International Study Center (TIC) 2018)

Table 1-2 (continued): Typical concentrations of critical minerals in various categories of e-waste.

Type of Electronic Device										
Critical Material	**Wind Turbines**	**Solar Panels**	**CRT-type Screens**	**LED/LCD Screens (Monitors and Notebooks)**	**LED/LCD Screens (Televisions and Other)**	**Cell Phones**	**Electric Vehicle Magnets**	**Computers**	**Medical Devices**	**References**
Tin		0.116 g 0.02 %	32 g* 1.0078 %^		18 g*	1.0874-3.075 % 1 g		4 %@	Trace^	(Buechler et al. 2020; Cucchiella et al. 2015; Diaz et al. 2016; Sica et al. 2018; Singh, Li, and Zeng 2016; Quinn et al. 2020; Sodhi and Reimer 2001)
Titanium			0.0157 %^			0.1332 %			37 %* 80-99 %^	(Buechler et al. 2020; Singh, Li, and Zeng 2016; Goodman 2019; Quinn et al. 2020)
Tungsten					0.00915 %*	0.0175 %				(Buechler et al. 2020; Ioannis Bakas and Baxter 2016)
Zinc	5500.0 kg/MW	0.4 g 0.04 w%	8.6 g* 2.2046 %^			1-4 g		1 %@		(Cucchiella et al. 2015; International Energy Agency (IEA) 2021; Sica et al. 2018; Singh, Li, and Zeng 2016; Bilesan et al. 2021)
Platinum Group Elements										
Iridium						0.000695 %			10 %@	(Buechler et al. 2020; Geddes and Roeder 2003)
Palladium			0.0003 %^	0.0099 %@^	0.044 g* 0.00061 %$ 0.0019 %@*	0.00225-0.6215 % 0.009-0.015 g		0.0005 %@^	~1 %^	(Buchert et al. 2012; Buechler et al. 2020; Cucchiella et al. 2015; Diaz et al. 2016; Ioannis Bakas and Baxter 2016; Singh et al. 2018; Singh, Li,

Table 1-2 (continued): Typical concentrations of critical minerals in various categories of e-waste.

Type of Electronic Device										
Critical Material	**Wind Turbines**	**Solar Panels**	**CRT-type Screens**	**LED/LCD Screens (Monitors and Notebooks)**	**LED/LCD Screens (Televisions and Other)**	**Cell Phones**	**Electric Vehicle Magnets**	**Computers**	**Medical Devices**	**References**
										and Zeng 2016; B. Woodward 2012)
Platinum						0.7257 % 0.004 g		0.0005 %[@^]	Varies[@]	(Buechler et al. 2020; Cucchiella et al. 2015; Cowley 2011; O'Brien et al. 2010; Ogunniyi and Vermaak 2009)
Ruthenium			0.0016 %^							(Singh, Li, and Zeng 2016)
Rare Earth Elements + Yttrium										
Cerium				0.2-0.680 mg^	0.3-4.500 mg* <0.001-0.005 g[$]	0.002611 %				(Buchert et al. 2012; Buechler et al. 2020; Cucchiella et al. 2015)
Dysprosium	2-8.19 %*					0.008639-0.0137 %	7.5 %			(Buechler et al. 2020; Diaz et al. 2016; Hart 2013; Hoenderdaal et al. 2013; Braeton J Smith and Eggert 2016; Venkatesan et al. 2018; Pavel, Thiel, et al. 2017)
Europium			0.0002 %	0.06-1.20 mg^ 0.03-0.13 mg[&]	0.09-8.10 mg* <0.001-0.008 g[$]	0.000242 %				(Buchert et al. 2012; Buechler et al. 2020; Cucchiella et al. 2015; Singh, Li, and Zeng 2016)
Gadolinium	0.15 %*			0.095-1.50 mg^ 0.011-0.75 mg[&]	<0.001-0.002 g[$]	0.0026 %				(Buechler et al. 2020; Cucchiella et al. 2015; Venkatesan et al. 2018)

Table 1-2 (continued): Typical concentrations of critical minerals in various categories of e-waste.

Type of Electronic Device										
Critical Material	**Wind Turbines**	**Solar Panels**	**CRT-type Screens**	**LED/LCD Screens (Monitors and Notebooks)**	**LED/LCD Screens (Televisions and Other)**	**Cell Phones**	**Electric Vehicle Magnets**	**Computers**	**Medical Devices**	**References**
Lanthanum				1.00 mg^ 0.11 mg&	6.80 mg* 0.007 %*					(Buchert et al. 2012; Cucchiella et al. 2015)
Neodymium	22.21-30.2 %*					0.0818-0.1372 %	24 %			(Buechler et al. 2020; Diaz et al. 2016; Hart 2013; Hoenderdaal et al. 2013; Braeton J Smith and Eggert 2016; Venkatesan et al. 2018; Pavel, Thiel, et al. 2017)
Praseodymium	0.76-7 %*				< 0.001 g*	0.0095-0.0169 % 0.01 g	1-6 %			(Buechler et al. 2020; Cucchiella et al. 2015; Diaz et al. 2016; Braeton J Smith and Eggert 2016; Venkatesan et al. 2018; Pavel, Thiel, et al. 2017)
Samarium						0.000981 %				(Buechler et al. 2020)
Terbium	1 %*			0.340 mg^ 0.038 mg&	2-2.300 mg*		1 %			(Buchert et al. 2012; Cucchiella et al. 2015; Hart 2013; Pavel, Thiel, et al. 2017)
Yttrium			0.0002 %^	3.2-16.0 mg^ 1.6-1.8 mg&	4.9-110 mg*					(Buchert et al. 2012; Cucchiella et al. 2015; Singh, Li, and Zeng 2016)

Notes: Grey shading = no information found. % = weight percent (w/w%). Values are for the entire device (with the battery removed, if applicable) unless attributed to a specific component. Ranges are provided where possible; single values are displayed if only one source was found. Values reported in different units (i.e., percents and masses) are from different sources and are not necessarily equivalent.

1.2. Location and Purpose of Critical Materials in Electronics

1.2.1. Aluminum

Aluminum is widely utilized in electronics. In wind turbines, aluminum is found in alloys in a variety of components, including the towers, nacelles, gearboxes, rods, and end rings (Demir and Taşkın 2013; Wilburn 2011). Aluminum is the main component of solar panel frames (Weckend, Wade, and Heath 2016; H. Cui et al. 2022), and small amounts of it may also be found in their metallization pastes (H. Cui et al. 2022). In CRT-type screens, it may serve both structural and conductivity purposes, as it may be found in the screen housing, printed wiring boards (PWBs), and connectors (Singh, Li, and Zeng 2016). Cell phones sometimes utilize aluminum in their frames and in the form of aluminum nickel cobalt (alnico) magnets (Christian et al. 2014).

1.2.2. Arsenic

Arsenic is often present in photovoltaic (PV) panels in the form of gallium arsenide (GaAs) (US Geological Survey 2019), a semiconductive material also found in the integrated circuits in cell phones (Christian et al. 2014). In CRT screens, arsenic can be found in doping agents in transistors and PWBs (Singh, Li, and Zeng 2016). Cell phones also utilize arsenic in their radio frequency and power amplifiers (Jenness et al. 2016).

1.2.3. Cobalt

Cobalt is present in many electronics – its leading global use is in lithium-ion batteries (US Geological Survey 2023), but it can also be found in CRTs as an electrode (Innocenzi et al. 2013; M. Li and Lu 2020). Beyond its electronic properties, cobalt is often used to produce hard and soft magnets (Strnat and Strnat 1991). Particularly, samarium cobalt alloyed magnets are widely used in electronics and aerospace due to their excellent high temperature performance (Yi 2014), while other cobalt-based magnets are used in computer hard drives and chips (Coey 1995).

1.2.4. Gallium

In electronics, gallium is primarily used in LEDs and semiconductors. PV panels often contain gallium in the form of copper indium gallium diselenide (CIGS) (US Department of Energy Office of Energy Efficiency & Renewable Energy) or GaAs (US Geological Survey 2019) semiconductors. LED screens may utilize indium gallium nitride (InGaN) in their semiconductor chips (Buchert et al. 2012). Cell phones may use forms of gallium for their LED backlighting (Singh et al. 2018) and GaAs in their semiconductor components and integrated circuits (Christian et al. 2014; Foley et al. 2017).

1.2.5. Indium

PV panels use indium in CIGS or copper indium diselenide (CIS) semiconductors (US Department of Energy Office of Energy Efficiency & Renewable Energy). In CRT-type screens, indium may be found in transistors, rectifiers, and PWBs (Singh, Li, and Zeng 2016). Other types of screens, such as LED and LCD screens, use InGaN semiconductor chips (Buchert et al. 2012) and indium tin oxide (ITO) as electrode materials for transparent circuits (Christian et al. 2014; Buchert et al. 2012; Jenness et al. 2016).

1.2.6. Nickel

Nickel primarily serves structural purposes in electronic devices. In wind turbines, it is often associated with stainless steels in ladders and other safety features, such as control panels and fasteners (Coates 2021). It also may be present in small amounts in low alloy steels in the wind turbine gearbox to decrease weight while increasing material strength (Coates 2021). In CRT-type screens, nickel may be used in the screen housing, PWBs, or even in the CRTs themselves (Singh, Li, and Zeng 2016). Cell phones make limited use of nickel externally due to the prevalence of nickel sensitivities, but cell phone radiofrequency cans may contain nickel (Christian et al. 2014). Additionally, cell phones sometimes utilize alnico magnets (Christian et al. 2014).

1.2.7. Niobium

Niobium finds some use in electronics as a capacitor or in optoelectronics as a crystal (Mohammadi, Abdizadeh, and Golobostanfard 2013; Yoon et al. 2009). Niobium alloyed with titanium makes up the magnetic coil in magnetic resonance imaging (MRI) machines (Savage 2013). Beyond its use as a magnet, niobium often makes up piezoelectronics and can be used in lasers (Chauhan et al. 2016).

1.2.8. Platinum Group Elements (PGMs)

1.2.8.1. Ruthenium

In electronics, ruthenium is generally used in resistive circuits, electrical contacts (Royal Society of Chemistry 2023), and PWBs (Singh, Li, and Zeng 2016).

1.2.8.2. Palladium

Palladium’s primary use in electronics is in printed circuit boards (PCBs) and PWBs, particularly in their capacitors and contacts (Buchert et al. 2012). In older cell phones, palladium has also been used in leadframe finishes (Christian et al. 2014).

1.2.8.3. Iridium

Information on the iridium content of current electronics and electronic waste was scarce at the time of writing. However, the market for organic LED (OLED) screens has been growing significantly in recent years (Tremblay 2016). OLED displays often utilize iridium (III) complexes for their red and green emitters (Y. Zhang and Qiao 2021), so it is reasonable to suggest that future e-waste will contain an increased concentration of iridium. Small amounts of iridium can also be found in medical devices, particularly if it is alloyed with platinum and used as an electrode in defibrillators (B.K. Woodward 2014).

1.2.8.4. Platinum

Platinum is an important metal for several industries, including use in consumer electronics and medical devices. Platinum is vital for microelectronics, where it is used for electric contacts, electrodes, resistors, and capacitors (Davey 1985). Beyond its electrical properties, platinum is often doped into fiberglass, LCDs, and can be used to increase the magnetism of cobalt magnets (Kozhevnikov, Donnio, and Bruce 2008).

1.2.9. Rare Earth Elements (REEs)

REEs are present in a variety of electronic devices. Figure 1-1 illustrates the REEs commonly found in five of the major categories covered by this report: LED/LCD screens, electric vehicles, wind turbines, computers, and cell phones.

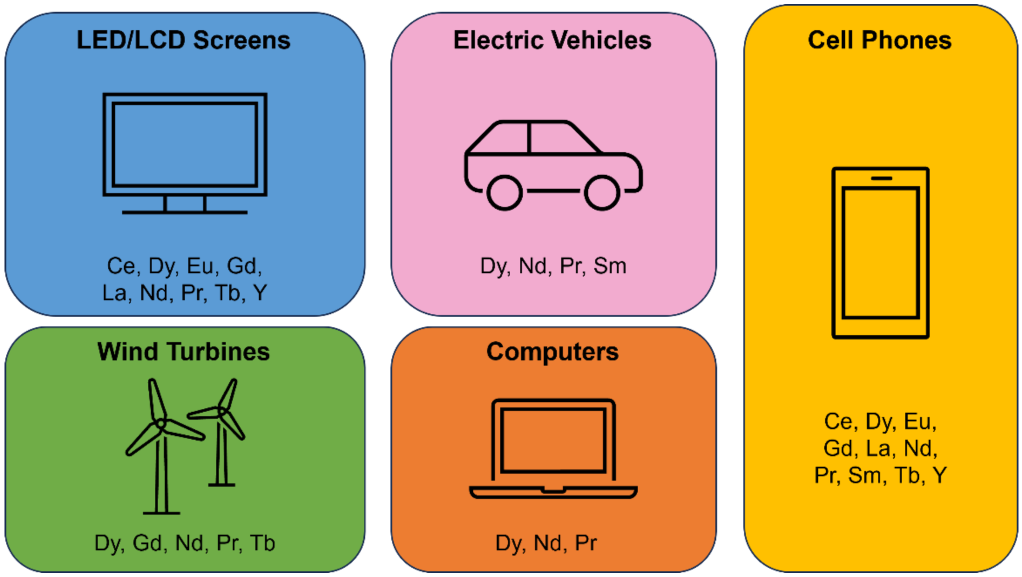

Figure 1-1: REEs commonly found in five categories of electronics.

1.2.9.1. Cerium

Cerium is often utilized in the form of $CeMgAl_{11}O_{19}$ in the support matrix for luminescent materials in LED/LCD screens and cell phones (Singh et al. 2018; Buchert et al. 2012).

1.2.9.2. Dysprosium

Dysprosium is frequently used to replace small amounts of neodymium in neodymium iron boron (NdFeB) magnets to increase the magnets' temperature stability (Hoenderdaal et al. 2013), and to increase magnetic coercivity (Xiaoli et al. 2016). Thus, it is typically found in the same electronic devices as neodymium; wind turbines (Hoenderdaal et al. 2013), computers (Hoenderdaal et al. 2013), electric vehicles (L. Chen et al. 2015), television screen speakers (Lixandru et al. 2017), and cell phone speakers (Christian et al. 2014) all utilize dysprosium-containing magnets.

1.2.9.3. Europium

In electronics, europium is often employed for luminescent purposes. In CRT-type screens, it may be found in phosphor activators (Singh, Li, and Zeng 2016), and in LED/LCD screens, it can either be used as an activator or as a dopant (Buchert et al. 2012). Cell phones also utilize europium in phosphors (Christian et al. 2014), particularly in their LED backlighting (Singh et al. 2018).

1.2.9.4. Gadolinium

Gadolinium may be found in small quantities in NdFeB magnets (Venkatesan et al. 2018). Thus, it can be found in wind turbines (Venkatesan et al. 2018) and cell phones (Christian et al. 2014). Gadolinium is also used in luminescent substances and/or their support matrixes in LED/LCD screens/monitors (Buchert et al. 2012), and cell phones (Singh et al. 2018).

1.2.9.5. Lanthanum

Lanthanum is often utilized in the support matrix for luminescent materials in LED/LCD screens, typically in the form of La_2O_3 (Buchert et al. 2012). It is also found in the glass of cell phone camera lenses (Christian et al. 2014), as La_2O_3 increases alkali resistance (Los Alamos National Laboratory 2023).

1.2.9.6. Neodymium

Neodymium is primarily used in electronics in the form of strong permanent magnets. Wind turbines utilize NdFeB magnets in their generators (Hoenderdaal et al. 2013), computers utilize them in their hard drives (Honshima and Ohashi 1994), electric vehicles rely on them for their engines (Riba et al. 2016), and television screens (Lixandru et al. 2017) and cell phones (Singh et al. 2018) use neodymium-based magnets in their speakers.

1.2.9.7. Praseodymium

Often, praseodymium replaces small amounts of neodymium in strong permanent magnets to reduce costs (Imholte et al. 2018), increase resistance to corrosion (Hart 2013), and increase magnetic coercivity (Braeton J Smith and Eggert 2016). Thus, it is typically found in the same electronic devices as neodymium, which include wind turbines (Imholte et al. 2018), television screen speakers (Lixandru et al. 2017), and cell phone speakers (Singh et al. 2018; Christian et al. 2014).

1.2.9.8. Samarium

Samarium can be found in cell phones (Christian et al. 2014) and electric vehicles (Bailey et al. 2021) in the form of samarium-cobalt permanent magnets.

1.2.9.9. Terbium

Terbium is occasionally added to NdFeB magnets in place of dysprosium to increase the magnets' maximum operating temperature (Imholte et al. 2018). However, this substitution is only performed if terbium becomes cheaper than dysprosium (Pavel, Lacal-Arántegui, et al. 2017). Thus, terbium can be found in wind turbine magnets (Imholte et al. 2018), but generally only in small quantities. Terbium is also used in luminescent materials in LED/LCD screens (Buchert et al. 2012) and cell phones (Christian et al. 2014).

1.2.9.10. Yttrium

In CRT-type screens, yttrium is often present in the form of a red phosphor emitter (Singh, Li, and Zeng 2016). In LCD/LED television screens and monitors, yttrium is used in the support matrix for luminescent materials in the form of Y_2O_3 or yttrium aluminum garnet (YAG) (Buchert et al. 2012). Cell phones also make use of yttrium in their LED backlighting (Singh et al. 2018) and phosphors (Christian et al. 2014).

1.2.10. Tantalum

Tantalum is ubiquitous in many electronics due to its superior capacitance, which allows it to hold more charge than other materials. As a result, it is used to produce electrical circuits, capacitors, and resistors in microelectronics, computers, and mobile phones (US Geological Survey 2023). In the medical industry, it is often used in shock coils for defibrillators (Frank and Richard 2005).

1.2.11. Tin

Tin is primarily used in electronics as a component in solder alloys. PV panels (Zarmai et al. 2016), CRT-type screens (Singh, Li, and Zeng 2016), and cell phones (Christian et al. 2014; Jenness et al. 2016) all utilize tin in solder. Cell phones also utilize tin in the form of ITO, which is used to create transparent circuits (Jenness et al. 2016).

1.2.12. Titanium

In PV panels, titanium is occasionally present in the form of TiO_2, which is used in anti-reflective coatings (Sica et al. 2018). In CRT-type screens, titanium may be used as a pigment and/or as an alloying agent for the aluminum housing (Singh, Li, and Zeng 2016). Cell phones utilize barium titanate in their acoustic devices and, less frequently, titanium metal in coatings in their integrated circuits (Christian et al. 2014). In the medical field, titanium is a fundamental material; it is used in implantable medical devices due to its corrosion resistance and biocompatibility (Valiev et al. 2020), and it is alloyed with niobium to make the magnetic coil for MRI machines (Savage 2013).

1.2.13. Tungsten

In cell phones, tungsten is often used as a heat sink and to provide the mass required for vibration (Singh et al. 2018; Christian et al. 2014; Jenness et al. 2016).

1.2.14. Zinc

In both wind turbines and solar panels, zinc coatings are used to prevent rust (International Zinc Association 2023). Solar panels may also use zinc in the form of magnesium zinc oxide in p-n heterojunction structures or as zinc telluride, which is used for electrical contacts (US Department of Energy Solar Energy Technologies Office). In CRT-type screens, zinc may be found in batteries, phosphors, PWBs, and the CRT itself (Singh, Li, and Zeng 2016).

1.2.15. Defense Applications of Critical Materials

CMs are essential for US defense. In addition to the more general applications described above, such as permanent magnets, screens, and semiconductors (which are also used for military purposes), CMs fill a variety of defense-specific roles. Often, CMs serve structural purposes (e.g., aluminum in airframe material for aircraft and niobium, nickel, and cobalt in superalloys), but their uses also include ammunition (e.g., tungsten), night vision goggles (e.g., tantalum), and guided missiles (e.g., iridium) (US Defense Logistics Agency 2023). REEs are used in satellite communications, guidance systems, aircraft structures, and more (National Energy Technology Laboratory 2019), REEs are the building blocks for many defense technologies. Notably, each modern F-35 aircraft requires approximately 920 pounds of REEs (Parman 2019).

1.3. Summary

Using the information collected in this chapter as a guide, a refined list of the 32 CMs that are most relevant to e-waste was developed. The select list of CMs was identified based on a variety of factors such as availability, market demand and price, import reliance and the concentration of CM in electronic devices. This list includes aluminum, arsenic, gallium, indium, nickel, tantalum, tungsten, titanium, tin, PGMs (platinum, palladium, rhodium, ruthenium, osmium, and iridium), and REEs (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium, and yttrium). For the purposes of this report, niobium and cobalt were not researched further. Cobalt's leading global use is in lithium-ion batteries, which are outside the scope of this report, and niobium's concentration is negligible in the selected categories of e-waste aside from MRI magnets, which only constitute a small fraction of the global e-waste stream.

Some of the selected 32 CMs – namely, a handful of the PGMs and REEs – were not specifically covered in Chapter 1 because information about their concentrations in e-waste was not readily available. However, because the terminology “platinum group metals” and “rare earth elements” in the literature refer to the full groupings, these elements were still included in the refined list.

2.0 E-waste Supply Chain and Recycling

2.1. Introduction

E-waste is one of the fastest growing waste streams. The total mass of e-waste generated globally in 2019 was 53.6 million metric tons (Mt), an increase from the 41.8 Mt reported in 2014 (Pan, Wong, and Li 2022). The UN's Global e-waste monitor (Forti V. 2020) predicts that it will reach 74 Mt by 2030 (Figure 2-1). E-waste is heterogeneous and diverse, with many component materials ranging from precious metals (e.g., platinum group metals and silver), to toxic additives (e.g., lead and cadmium), to plastics. The market size of e-waste is forecasted to reach US $99.67 billion, growing at a compound annual growth rate of 16.2% by 2030 according to a research report by Market Research Future (MRFR) (Market Research Future 2022). Increased volumes of e-waste not only contribute to the increasing environmental burden when disposed of in landfills or incinerated, but also to the wasting of valuable material resources that could eventually be added back into the supply chain.

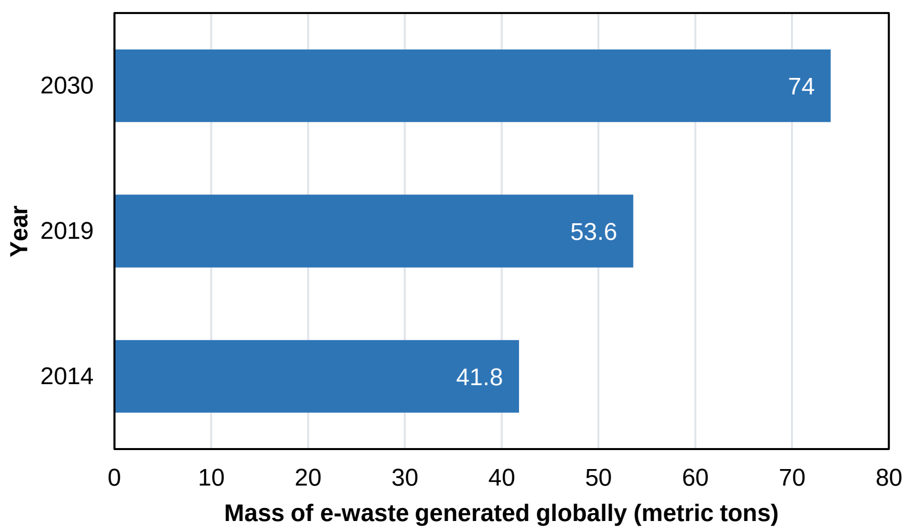

Figure 2.1: E-Waste projections [Data obtained from (Forti V. 2020)].

Circularity of e-waste is a critical part of reducing environmental burden and addressing domestic material supply chain security. US-defined CMs are lacking in domestic supply chain security and are needed for US defense and/or clean energy technologies. CMs are utilized in electronics manufacturing and in many other industries (e.g., batteries, electric vehicles, wind turbines, alloying, and defense). There is an enormous opportunity in identifying various avenues to recover potential raw materials and generate economic value from e-waste. In 2019, the value of raw materials potentially recoverable from e-waste was estimated to be $57 billion (Pan, Wong, and Li 2022). Carbon dioxide (CO_2) emissions can also be reduced by the recycling and recovery of e-waste CMs. For example, the recovery of aluminum, copper, and iron has resulted in a reduction of 15 Mt of CO_2 emissions (Pan, Wong, and Li 2022).

2.2. Recycling

The benefits of recycling include limiting the use of natural resources, minimizing waste, and promoting sustainable economic development. All of these contribute to circularity, where recovered materials can be reused in the same product (closed-loop) or other products (open-loop), ideally resulting in little to no overall waste. The ultimate circularity is when a product chain is completely closed and materials can be recovered and reapplied (Potting et al. 2017). There are multiple levels of circularity as illustrated in Table 2-1 (Potting et al. 2017). The R0 through R9 circular economy strategies help with reducing environmental burden and may assist in the onshoring of domestic supply chain for valuable CMs.

Table 2-1: Circular economy strategies [Adapted from (Potting et al. 2017)].

	Circular Economy	Strategies	Description
Smarter product design	R0	Refuse*	Product innovation – offer different product with same function
	R1	Rethink	Product innovation
	R2	Reduce	Consume fewer natural resources and materials
Extending lifespan of product	R3	Re-use	Reuse products still in good condition
	R4	Repair	Repair products so it can be used
	R5	Refurbish	Restore old products for use
	R6	Remanufacture	Use discarded parts in new product with the same function
	R7	Repurpose	Use parts or products in a different function
Recovery of materials and application	R8	Recycle	Process materials to obtain the same or lower quality
	R9	Recover	Incinerate materials for energy recovery

*To avoid a product in favor of a more environmentally friendly option.

Lead-acid batteries have a recycling rate of 99% in the US and can provide insights that may inform a successful e-waste circularity strategy. Part of the success may be attributed to strict regulations and the fact that landfills do not accept them (Heath et al. 2022). However, policy and regulation strategies may or may not be feasible to drive the recycling of e-waste. Aluminum has a similarly successful recycling rate — about 75% of the raw aluminum that has been produced globally has been recycled and is still in use (Heath et al. 2022) — but a different driver for circularity. Recycling aluminum expends only 2.8 kWh/kg and 0.6 kg of CO_2 in comparison to 45 kWh/kg and 12 kg of CO_2 for the manufacturing of raw aluminum (Raabe et al. 2022). This provides a significant economic and environmental benefit in addition to resource conservation. However, factors such as government regulations, manufacturer responsibilities, market demand for materials, consumer behavior, and connections between supply chain segments (e.g., connecting recyclers and material end users) vary widely depending on the products and materials in question. As such, caution should be exercised when trying to apply lessons from analogous industries to e-waste circularity challenges.

2.2.1. Importance of Critical Materials to Supply Chain

Many recyclers only target precious metals, such as gold and silver, and discard CMs, such as REEs, graphite, gallium, indium, arsenic, and more. These CMs are important for clean energy technologies (e.g., rare earths in the wind energy and electric vehicle industries) and defense applications (e.g., rare earths for satellite communications and guidance systems), and they are considered critical because of their high import reliance. Dependence on foreign suppliers makes the US vulnerable to supply chain disruptions. However, the e-waste generated by the US containing CMs provides an opportunity to secure domestic supply chains. For example, the total mass of indium, gold, and plastics contained in e-waste exceeded the cumulative demand for each of those materials contained in new products being sold in 2018 (Althaf, Babbitt, and Chen 2021). There is an urgent need to view e-waste management and material recovery as a valuable resource for domestic supply chains and manufacturing.

2.2.2. Challenges

Some of the challenges in e-waste circularity are listed below:

- ***Recycling infrastructure***: There is a lack of recycling infrastructure for e-waste, which leads to poor disposal habits by consumers.
    - ***Collection centers:*** The existing e-waste disposal infrastructure is not efficient in capturing and channeling household e-waste to recyclers implementing e-waste recovery. A clear and defined network of collection centers and distributors is essential to a successful recycling and recovery process.
    - ***Sorting***: Detection and sorting are necessary to enable scaling of consumer e-waste CM recovery and recycling. Sorting is required and practiced to some extent at waste reclamation facilities. Current sorting and recycling processes are often designed to accommodate single materials (using a linear material model), and the pre-separation of objects composed of multiple recyclable materials presents economical and logistical challenges. These objects are often discarded. Advanced tools/sensor technologies are needed to allow rapid classification at scale and adequately recover materials. This is a large barrier preventing e-waste materials circularity.
    - ***Responsibility for end of life:*** There is no defined responsibility for products at end of life. There are a number of social and economic challenges to determining where responsibility falls (e.g., manufacturer, recycler, consumer).
    - ***Electronic recyclers***: Local communities are often not aware of nearby e-waste recycling facilities. One of the ways to create a market for e-waste recyclers is to develop an awareness of the market value of e-waste to all the players in the e-waste supply chain (manufacturers, distributors, consumers, recyclers, etc.).
- ***Regulations***: The Environmental Protection Agency (EPA) promotes the sustainable practice of electronics which includes a commitment towards encouraging environmentally preferable design and responsible management of used electronics under the National Strategy for Electronics Stewardship (US Environmental Protection Agency 2023). The EPA promotes two third-party certification programs for electronic waste recyclers in the US: Responsible Recycling Standard for Electronic Recyclers (R2) and the e-Stewards Standard for Responsible Recycling and Reuse of Electronic Equipment® (e-Stewards®). There is a need for additional training and guidance materials for all stakeholders to grow their knowledge base on e-waste management. Stricter enforcement in e-waste management, specifically for collection, sorting, dismantling, and implementation of recovery treatment can help move the industry further into a circular economy.
- ***Incentives:*** There is no current significant economic incentive for recyclers to collect themselves and pay fees for shipping and handling. Consumers may dispose of the products either at a landfill or at a designated recycling center based on their locations, but there is no incentive provided for consumers to return for recycling. Manufacturers or

distributors are not positioned to collect the end-of-life (EOL) products in the existing infrastructure and are typically not economically incentivized either.

- ***Technology**:* The e-waste stream is complex and diverse. There is significant heterogeneity across the types of electronics and wide disconnects between manufacturers and recyclers, as upstream manufacturing has not been focused on downstream impacts such as recycling or reuse. Recovering materials is also challenging since materials are dispersed in various product components, and CM compositions can vary widely by year, manufacturer, and product line. Materials have varying compatibility with current recycling approaches. There are no technologies at commercial scale for comprehensively recovering CMs from e-waste. Chapter 4 describes current recovery efforts and technological advancements for a selection of CMs. Developing scalable technology innovations to recover CMs to provide widespread commercial gain has been a challenge. There is a need for technologies that comprehensively recycle products containing multiple valuable materials, rather than targeting a single CM or single component. For example, technologies exist that target magnets, printed circuit boards, LEDs, capacitors, and more – but these are all separate and unique from one another, making them challenging to deploy at the same time and on bulk products. There is also a need for technologies that can recover materials from products after all earlier circular strategies such as reuse, repair, and refurbishment are exercised.

2.3. End-of-Life (EOL) Management

EOL management of e-waste can be addressed in many ways, such as implementing concepts from the 10 recycling strategies (Table 2-1), improving sorting and screening technologies, and better defining infrastructure to route e-waste to recovery centers.

Table 2-1 presents a range of strategies ordered from high circularity (low R-number such as R0 or R1) to low circularity (high R-number such as R8 or R9). For example, R0, R1, and R2 are circularity strategies focused on smarter product design, which might be accomplished by incorporating fewer natural resources and materials. Similarly, R3, R4, R5, R6, and R7 are specific to extending product lifespan, emphasizing strategies to reuse, repair, refurbish, remanufacture, and repurpose products. R8 and R9 incorporate useful applications of EOL materials that include recycling and recovering energy through incineration. Overall, strategies R8 and earlier are preferred in the waste hierarchy to increase circularity in e-waste (Coughlan, Fitzpatrick, and McMahon 2018).

As mentioned previously, one of the challenges in e-waste recycling relates to the difficulty of detecting and sorting materials. The use of a codifying process during product development and manufacturing would help in sorting and processing during EOL management. Development of fast screening techniques that identify signatures of certain waste for quick sorting/evaluation will expedite the movement of e-waste through the distribution link to the relevant recovery center.

The European Union has used the concept of Extended Producer Responsibility (EPR) to address EOL management since the 2000s. Many other developed countries like Japan, Australia and Canada have adopted the practice in recent years. EPR is an environmental strategy that makes the product manufacturer responsible for the entire life cycle of the product. The manufacturer is responsible for take back, recycling, and final disposal of the product (Khetriwal, Kraeuchi, and Widmer 2009). Some aspects of establishing a sustainable EPR based system involve organizing a capital network for collecting and taking back e-waste and ensuring compliance (Khetriwal, Kraeuchi, and Widmer 2009). EPR requires manufacturers to consider a sustainable reverse supply chain. This concept helps reduce environmental impact and places economic burden on manufacturers, which can often help drive economics towards one of more of the 9R strategies. EPR often encourages manufacturers to design innovative products with circularity in mind (R0-R2). An example of the Swiss e-waste management system is shown in Figure 2-2. Strong waste policies and a sound supply chain structure are crucial to successful EPR management (Corsini, Rizzi, and Frey 2017).

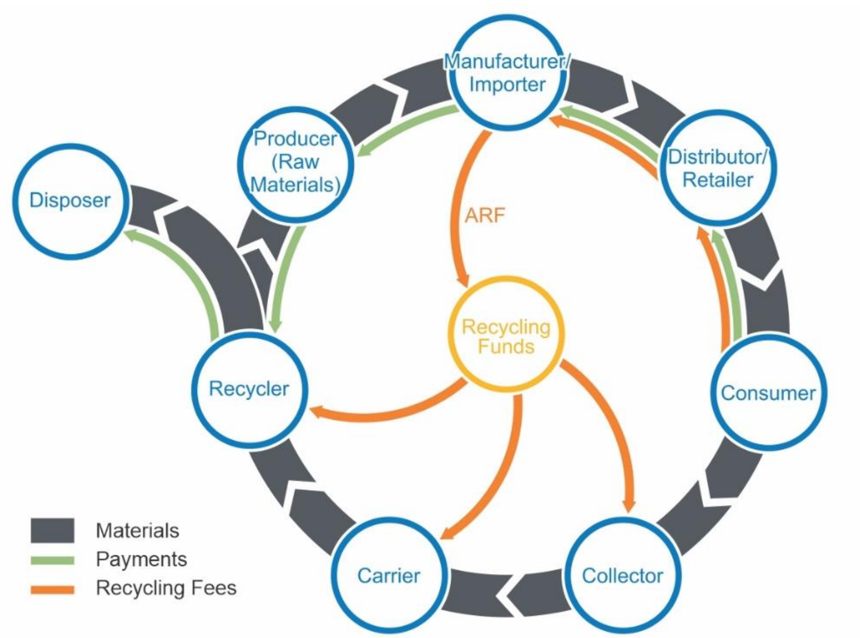

Figure 2-2: Extended Producer Responsibility [Figure adapted from (Khetriwal, Kraeuchi, and Widmer 2009)].

2.3.1. EOL Logistics

Collection and transportation of e-waste at EOL are important facets in improving circularity. There are costs associated with collection and shipping of e-waste to recyclers or collection centers that can impact economics and decision making for EOL materials. Consumer behavior plays a crucial role when the costs for collection and recycling are not assigned. These costs need to be determined and potentially shared by producers, distributors, municipalities, and consumers. A 2018 study (Nowakowski and Mrówczyńska 2018) examined e-waste collection and transportation methods for rural and urban settings. The study found that mobile collection (door to door e-waste collection) had the lowest impact on the environment (low emissions) and total cost in an urban setting when combined with waste pickup. However, mobile collection of e-waste in a rural setting can become cost prohibitive. The study recommended the consideration of placing a collection container in high traffic areas, such as town halls and schools.

An understanding of the geographical distribution of e-waste may be needed to determine the density of e-waste and eventually support an efficient system for collection and transportation. Social, economic, and environmental factors are all important factors in EOL management. A life cycle analysis model can be developed to understand the impacts of various collection models in a specific geographical setting to ensure minimum environmental impact. Public awareness can help in contributing to sound EOL management for e-waste.

2.4. Environmental Justice Implications

There is an opportunity to incorporate Justice40 guidance to help disadvantaged communities as part of developing new CM recovery technologies. Mine operations are often plagued by environmental, operational, and safety issues, and mining for CMs has a higher environmental footprint than CM recovery from e-waste. Recycling e-waste reduces the need for mining new CMs (which are often located near disadvantaged communities) and thus minimizes the negative impacts on disadvantaged communities. Additionally, e-waste exposure can be hazardous for human health. Using e-waste to recover CMs not only decreases the environmental burden when e-waste is discarded in landfills or incinerated but also prevents the health risk.

Creating more recycling centers and building recycling infrastructure can boost economic growth and create more jobs while meeting environmental justice considerations and improving resource efficiency. In 2019, only 17.4% of the e-waste produced globally was handled by formal waste management systems; the remaining 82.6% was not documented (World Health Organization 2021). Much of the e-waste generated in higher-income countries is shipped to lower income countries for informal processing (World Health Organization 2021). Developing robust recycling infrastructure and e-waste management policies in the US is thus globally responsible action.

2.5. Summary

Overall, a clear understanding of the supply chain and life cycle of electronic items is essential to build a methodology to address EOL management pathways while promoting circularity. E-waste management needs further innovation in upstream (manufacturing), mid-stream (reuse, repair, refurbish), and downstream (collection, sorting, recycling, recovery, and reuse) portions of the supply chain. Several important factors to achieving e-waste materials circularity are summarized below.

Infrastructure: A waste collection infrastructure for e-waste should be developed that considers the end-to-end supply chain structure and policies. Specifically, manufacturers, distributors, consumers, and recyclers need a well-defined supply chain network to enable recovery of valuable materials from e-waste. Quantifying and communicating the value of e-waste, along with understanding geographical information about collection and recycling centers, are crucial to promoting circularity.

EOL Management: Incorporating more of the strategies listed in Table 2-1 will pave the first step towards circularity in e-waste. Similarly, implementing EPR or similar responsibility-driven e-waste management techniques will move towards capturing and reusing the valuable CMs from e-waste.

Product Design: Better product design can extend product lifetime through modularity, wherein products can be broken into individual components for better incorporation of the R10 strategies. Devices should be designed with modular structure and recovery strategies in mind to maximize recycled content and facilitate easy repair, reuse, and refurbishment.

Technology Innovation: Developing technologies (1) for sorting and classification and (2) that can recover CMs from multiple components within a given product is likely to recover more materials and help tip the scales economically. Sorting and recovery technologies may be separate techniques but implemented in parallel or may be combined in a bulk technique without losing selectivity. A universal codifying process for new products would help speed up and reduce costs for sorting and processing, and as such innovations in fast screening techniques that identify signatures of certain waste are needed. Alternatively, open collaboration with manufacturers may provide product CM composition ranges to help train and improve sorting and screening technologies.

CM recovery technologies need to be improved to address multiple valuable CMs from a wide range of e-waste products. Additionally, current bulk e-waste recycling processes tend to employ mature techniques such as hydro- and pyrometallurgy, which have higher environmental footprints than newer techniques such as biometallurgy. A balance needs to be struck, where environmental impact and process economics are considered throughout research and development and scale-up stages.

End-User Markets: In some cases, recycling processes exist at scale, but materials are not connected with the proper end-user markets. For example, in the solar photovoltaic industry, materials such as glass, aluminum, and silicon can be recovered during recycling. However, not all materials are adequately connected with end-user markets for optimal reuse of materials and may be sold at a loss rather than at a profit. There is a need to connect various segments of the supply chain, especially reused materials, to ensure circularity.

Incentives: There is an opportunity to incentivize circular economy strategies if technologies can be developed and refined that minimize cost. Policies and legislation in conjunction with these innovations are crucial to improving the circularity of e-waste.

Consumer Behavior: Lastly, consumer behavior is a key component to the successful operation of any circular economy and may play a large role in turning the electronics industry from linear to circular.

3.0 E-Waste Metal Recovery

Because the world's demand for CMs is anticipated to increase by 400 to 600 percent in the coming decades (The White House 2022), interest in recovery from secondary sources such as e-waste has risen greatly in recent years (Hsu et al. 2019). However, different extraction technologies may be preferred depending on the material(s) in question due to a variety of factors, such as the material's typical concentration and/or form in e-waste. Additionally, differences in factors such as market price, import reliance, difficulty of extraction, and connection to material buyers lead to discrepancies in recovery efforts; some CMs are already being recovered in commercial-scale operations worldwide, while others are not recovered at all. Figure 3-1 summarizes the most prevalent methods in the literature for metal recovery from e-waste.

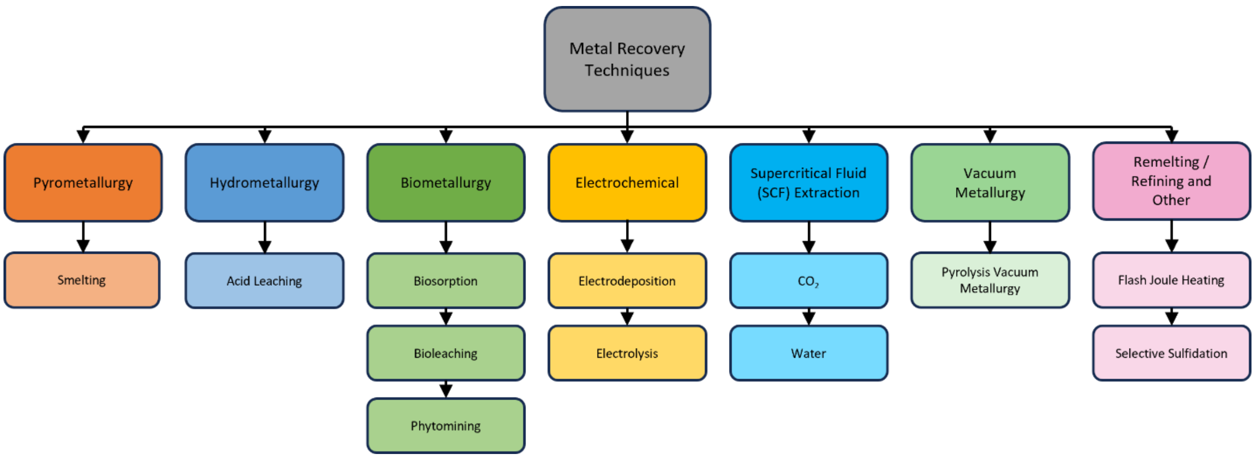

Figure 3-1: Techniques for metal recovery from e-waste and examples

3.1. Technologies

The following sections describe the most prevalent technologies used for metal recovery from e-waste.

3.1.1. Pyrometallurgy

Pyrometallurgy is a branch of extractive metallurgy that uses high-temperature methods to recover metals from source materials (Habashi ; Palanisamy et al. 2022). Pyrometallurgical techniques for metal recovery from e-waste generally begin by burning the plastics off the waste scraps in a furnace (L. Zhang and Xu 2016), which results in the volatilization of target metals (L. Zhang and Xu 2016) and the production of a slag containing impurities and refractory oxides (Jirang Cui and Zhang 2008). Due to its substantial energy requirements, pyrometallurgy is most suitable for sources with relatively high concentrations of target metals (Sun et al. 2017). High-temperature methods have the potential to generate toxic gases when plastics, which comprise 10 to 20 percent of e-waste streams by weight (Ramprasad et al. 2022), are burned (Espinosa, Moraes, and Tenório 2015). Emission control is a major concern when using pyrometallurgy for e-waste recycling.

3.1.2. Hydrometallurgy

Hydrometallurgy is commonly used in conjunction with pyrometallurgy in e-waste recycling facilities (Tabelin et al. 2021). Like pyrometallurgy, hydrometallurgy is a branch of extractive metallurgy; however, hydrometallurgy utilizes aqueous solutions to recover metals from source materials (Habashi). Hydrometallurgical routines for metal recovery from e-waste commonly require two steps: an extraction stage and a recovery stage (Kumari and Samadder 2022). The purpose of the extraction stage is to selectively dissolve target metals from solid e-waste, typically via acid leaching (Ramprasad et al. 2022). Then, a separation technique is applied in the recovery stage to obtain pure metals. Potential separation techniques may include solvent extraction, adsorption, and electrowinning (Kumari and Samadder 2022).

3.1.3. Biometallurgy

Biometallurgy is a broad term describing extractive and recovery processes based on interactions between metals and microorganisms (Zhuang et al. 2015). Techniques under this umbrella include biosorption, phytomining, and bioleaching (Brown et al. 2023). Biometallurgy is an alternative to pyro- and hydrometallurgy that is widely considered to be a more “green” recycling process for e-waste (Dutta et al. 2023). It can reduce processing costs, it consumes less energy (Dutta et al. 2023) and produces less hazardous waste (Brown et al. 2023) than pyro- and hydrometallurgy. It can achieve high recovery rates due to high selectivities (Olson, Brierley, and Brierley 2003; Brandl, Bosshard, and Wegmann 2001; Faramarzi et al. 2004; Yakoumis et al. 2021; Dutta et al. 2023).

3.1.4. Electrochemical

Often, methods for metal extraction from e-waste result in impure products that require further processing. Electrochemical techniques (ECs), which can selectively recover high purity (Ramprasad et al. 2022) metals from a waste stream, are a possible solution to this problem. These techniques, which include electrodeposition and electrolysis, exploit differences in electromagnetic properties to separate metals (Wu et al. 2022). Compared to hydrometallurgical processes, ECs consume a smaller amount of chemicals (Ambaye et al. 2020; Ramprasad et al. 2022), making them a potentially environmentally friendly alternative. ECs are also modular and scalable (Ramprasad et al. 2022), and this versatility is beneficial for a stream as diverse as e-waste. However, low selectivity is an issue when several species with comparable electrode potentials are present (Ramprasad et al. 2022). Additionally, ECs are generally coupled with other techniques to reduce their energy consumption (Ramprasad et al. 2022; Makarova, Soboleva, et al. 2020).

3.1.5. Supercritical Fluid (SCF) Extraction

Supercritical fluids (SCFs), such as water and CO_2, have low viscosities and high metal solubilities (Wu et al. 2022). These properties make them ideal for metal extraction from solids like e-waste. During treatment, liquid SCFs are used to leach metal ions from a solid waste stream; when the pressure in the system is released, the SCFs and dissolved ions are converted to gas, effectively separating them from the remaining solids (Wu et al. 2022). Large-scale studies of SCF for e-waste processing are limited, but the harsh conditions (namely, the high temperatures and pressures) required to create SCFs imply significant capital costs (K. Li and Xu 2019). For reference, a technoeconomic analysis of SCF extraction of REEs from coal ash estimated a 1390-liter supercritical CO_2 reactor to have a capital cost of $4.2 million (Das et al. 2018). Corrosion-resistant alloys are needed for SCF reactors (K. Li and Xu 2019; Hayward, Svishchev, and Makhija 2003; Kritzer 2004), and special reactor design considerations must be made to combat the accumulation of salts via precipitation (Hodes et al. 2004; K. Li and Xu 2019). These expenses are a major barrier to scaling up SCF processes.

3.1.6. Vacuum Metallurgy

Pyrolysis-vacuum metallurgy recovers metals in two steps, pyrolysis followed by vacuum metallurgy separation (Zhan et al. 2018). Outside of e-waste, vacuum metallurgy separation is used for metal purification, reduction of ore deposits, and alloy separation (Zhan et al. 2018). Vacuum processing allows boiling points of metals to be reduced, lowering energy consumption (Zhan et al. 2018). Additionally, using a vacuum sealed system limits the introduction of impurities resulting in high purity products (Zhan et al. 2018). Pyrolysis-vacuum metallurgy has the advantage of using less energy, favors high purity products, and limits exposure to harmful compounds (Zhan et al. 2018). At the point of writing, vacuum metallurgy is not used for commercial e-waste recycling.

3.1.7. Remelting / Refining

The goal of the remelt/refining process is to remove undesirable inclusions and repurify scrap metals (Capuzzi and Timelli 2018). In the remelting process, metals are heated followed by the addition of metal scrap (Capuzzi and Timelli 2018). In some processes, pretreatments such as compacting, or decoating is performed prior to remelting (Capuzzi and Timelli 2018). During the remelting process, impurities which melt lower than the target are separated, often as oxides or through evaporation (Capuzzi and Timelli 2018).

3.2. Summary

This chapter summarizes the most common technologies used for metal recovery. Chapter 4 will present recovery technologies specific to the 32 CMs identified in Chapter 1.

4.0 Critical Material Recovery Technologies

This chapter describes current recovery efforts and technological advancements for a selection of CMs: aluminum, arsenic, gallium, indium, nickel, tantalum, tungsten, titanium, tin, PGMs (platinum, palladium, rhodium, ruthenium, osmium, and iridium), and REEs (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium, and yttrium).

To obtain the information in this chapter, the following methodology was used. First, an initial search was performed by entering key words/phrases into a scholarly search engine, such as Google Scholar. These key words/phrases were generally in the format "(critical material name) recovery/extraction from electronic waste/e-waste". For instance, the phrase "aluminum recovery from electronic waste" may have been searched to gather initial information for aluminum. The most relevant results were examined, and if more detail was needed, sources cited by those articles were also reviewed. These findings were used to guide searches performed using non-scholarly search engines, which were used to collect information on specific companies recovering CMs from e-waste.

4.1. Aluminum

Aluminum is one of the most recycled materials in the world. The global aluminum recycling rate released by the International Aluminum Institute (IAI) in October 2020 is 76% (International Aluminium Institute 2020) as shown in Figure 4-1. Aluminum can be remelted and reused without the loss of its unique properties, making it one of the most circular commodities. Europe has the highest recycling rate of 81% for aluminum due to their stricter policies on waste management and processing; followed by North America at 57%. Technologies employed to recycle aluminum (also called secondary aluminum) include melting, refining, and then ingot casting. The recycling technology is significantly cheaper than the energy intensive mining, refining, and smelting of bauxite ore (Raabe et al. 2022). As mentioned in Chapter 2, the extraction of aluminum from ores expends a lot of energy in comparison to the energy involved in remelting aluminum scrap. Hence, recycling aluminum has both economic and environmental benefits when compared with raw material production.

Secondary aluminum is collected from several waste streams that are sorted and shredded into small pieces. The aluminum scrap is sorted into its alloy type prior to melting. There are several sorting mechanisms such as magnetic separation, air separation (to remove plastics, foams etc.), dense media separation, eddy current separation (to selectively recover aluminum), manual sorting, and hot crushing (to separate wrought from cast products) (Brough and Jouhara 2020). The scrap is stripped of coatings and surface finishes using centrifuges and de-coating machines (Brough and Jouhara 2020) followed by melting into a molten state.

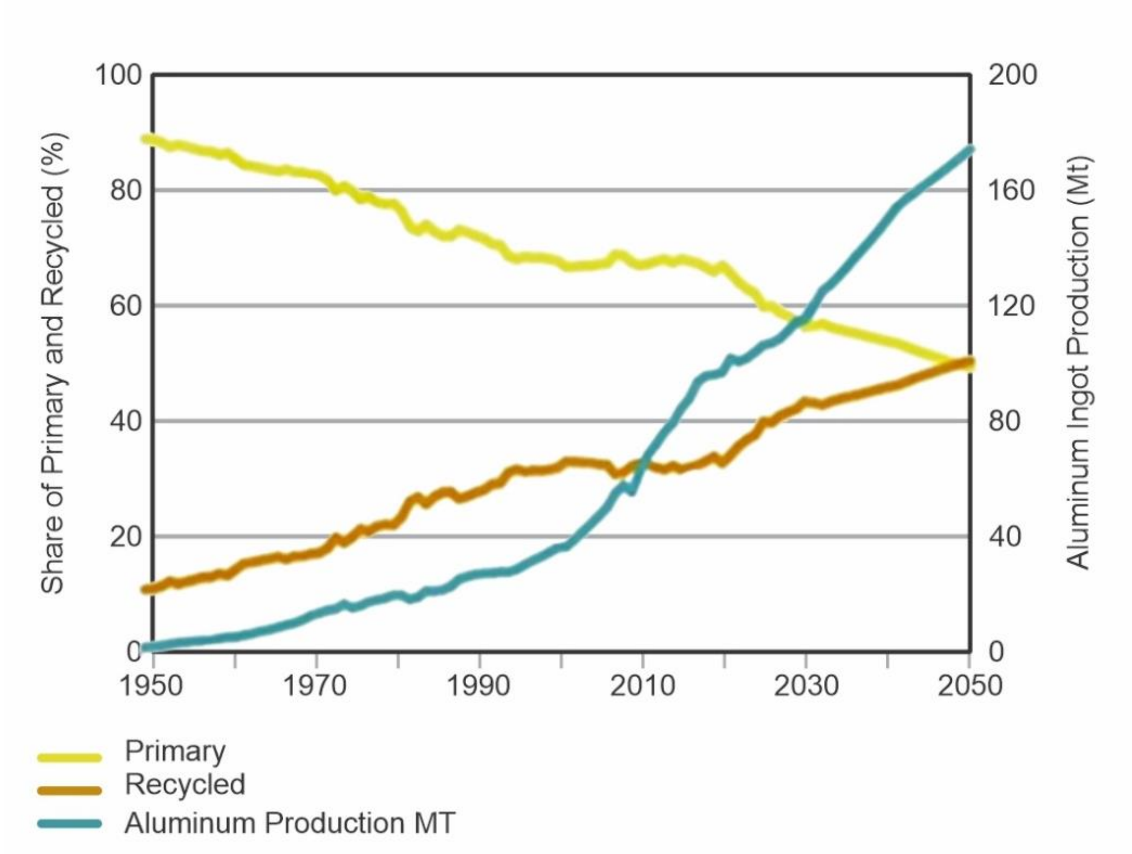

Figure 4-1: Development of primary and recycled aluminum through 2050 [Figure adapted from (Raabe et al. 2022)].

4.1.1. Remelting/Refining

Recycling of aluminum is done through either a refiner or a remelter. A refiner is used to produce casting alloys with the use of salts (Cullen and Allwood 2013). Remelting produces wrought alloy for extruded products without the use of salts. The melted alloy is then set into ingot molds and introduced back into the upstream supply chain. A simple overview of the recycling process is shown in Figure 4-2. It is important to note that the secondary aluminum does accumulate a lot of unwanted elements such as nickel, silicon, magnesium, zinc, lead, chromium, iron, copper, vanadium, and manganese (Gaustad, Olivetti, and Kirchain 2012). The secondary aluminum with unwanted impurities results in “downcycling” or creating products with lower value. The removal of these elements in the scrap stream requires different energy considerations.

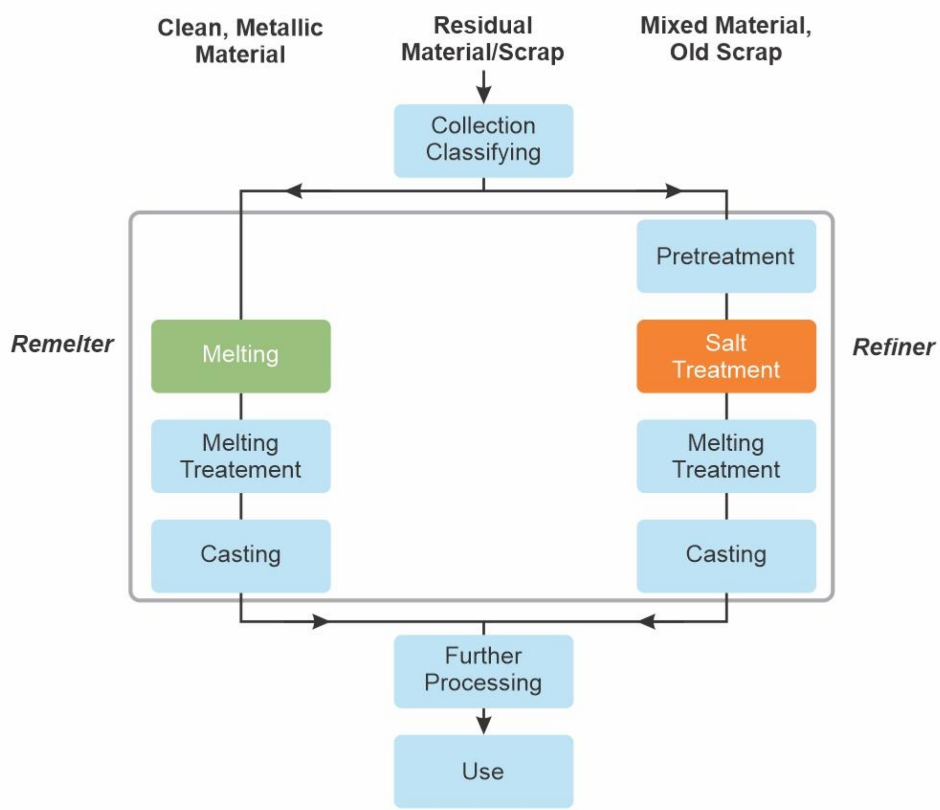

Figure 4-2: Recycling process for Aluminum [Figure adapted from (Raabe et al. 2022)].

A handful of companies appear to be extracting aluminum from specific e-waste products, though overall, it is unclear to what extent. Apple operates the Material Recovery Lab, a pilot-scale e-waste recovery facility in Texas which uses specialized robots to disassemble EOL iPhones and their Taptic Engines [1]. This disassembly process allows Apple to recover a variety of CMs from old devices, including aluminum [1, 2]. Apple states that its robots disassemble up to 1.2 million phones per year, but at the time of writing, no information was available on the total number of phones that have been processed [1]. Samsung operates the Asan Recycling Centre, which separates aluminum and other major metals from an array of waste electronics regardless of brand [3, 4]. In 2018, the Asan facility separated approximately 25 tons of major metals, but the company has not disclosed what percentage of this mass was aluminum [3]. Solar panel recyclers, such as SOLARCYCLE [5] and We Recycle Solar [6], recover the aluminum in solar panel frames, though the Solar Energy Industries Association (SEIA) only lists four companies as being capable of providing solar panel recycling services in the US, making this a relatively young industry [7].

4.2. Arsenic and Gallium

Gallium and arsenic are critical to modern electronics, often found together in LEDs, integrated chips, and semiconductor wafers (US Geological Survey 2023). Though alternatives exist for some applications, no effective substitutes exist for GaAs based integrated chips (US Geological Survey 2023). Despite its importance, neither gallium nor arsenic have been produced in the US since the 1980s, resulting in 100% import reliance for these metals (US Geological Survey 2023). While recycling would be a valuable alternative to raw material production, GaAs containing electronics are not commercially recycled due to gallium's disparate nature and arsenic's intrinsic toxicity (Umicore Precious Metals Refining 2023c). Outside of electronics, gallium is successfully recycled from wafer scrap and impure metals (Cheng et al. 2019). Sturgill recycles gallium and arsenic from wafer polishing wastewater by precipitating the elements through pH adjustment (Sturgill, Swartzbaugh, and Randall 2000). Beyond that, very few recycling processes are being investigated or implemented to recycle gallium and arsenic directly from waste wafers or integrated chips.

4.2.1. Pyrolysis-vacuum Metallurgy and Hydrothermal Buffering

Academically, pyrolysis-vacuum metallurgy (Zhan et al. 2018) and hydrothermal buffering method (HBM) (Zhan et al. 2020) show promise for recovering both gallium and arsenic from GaAs chips and wafers. Pyrolysis-vacuum metallurgy recovers gallium and arsenic at an efficiency of 95% by heating waste to 1000 °C under a vacuum of ~20 Pa for 60 minutes (Zhan et al. 2018). Pyrolysis-vacuum metallurgy has the advantage of using less energy, favoring high purity products, and limiting exposure to arsenic (Zhan et al. 2018). However, organics present may oxidize some gallium to their oxides using this method, and a sufficient temperature gradient must be achieved to completely separate gallium and arsenic (Zhan et al. 2018). HBM is a hydrometallurgical method developed to recycle GaAs chips (Zhan et al. 2020). In HBM, an oxidant is used in the presence of a phosphate buffer to decompose GaAs under hydrothermal conditions (Zhan et al. 2020). Using this method, recovery rates of 99.9% and 95.5% were achieved for gallium and arsenic, respectively (Zhan et al. 2020). HBM appears to be an efficient and environmentally friendly method to efficiently recover gallium and arsenic from integrated chips. At the time of writing, there are no commercial operations for recycling gallium and arsenic from GaAs e-waste.

4.3. Nickel

Nickel is a relatively abundant transition metal and is a staple across industries for use in batteries (Murdock, Toghill, and Tapia-Ruiz 2021), steel (Reck et al. 2008), electronics (Barceloux and Barceloux 1999), anti-corrosion technology (Yasin et al. 2018), and catalysis (Ananikov 2015). As a result, nickel is essential for building infrastructure, sustainable energy, and chemical production. Despite producing over 18,000 tons of nickel domestically, the US was still 56% import reliant in 2022 (US Geological Survey 2023). Up to 68% of the nickel in consumer products is recycled, the majority coming from the steel industry and its popularity among commercial recyclers including Umicore, Cohen, and Newton Technology (Umicore Precious Metals Refining 2023d; Newtech Recycling 2023). As a result, there is little focus on recycling nickel from e-waste, such as capacitors, circuit boards, and wiring. In these products, nickel is rarely a primary target, instead being recycled incidentally during the process of recovering more valuable metals (Hao et al. 2020). During pyrometallurgical and hydrometallurgical processes, nickel can be separated and purified by electrorefining, precipitation, adsorption, or extraction (Abdelbasir et al. 2018).

4.3.1. Pyrometallurgy

Commercial recyclers, including Umicore and Boliden, often include e-waste in their high temperature smelting and can recover nickel and other metals of interest in the slag phase and purify further through electrorefining (Jirang Cui and Zhang 2008; Dutta et al. 2023). Pyrometallurgy is preferred for commercial recyclers because it allows them to combine several waste streams, efficiently remove organic additives, and recover several metals using one process (Jirang Cui and Zhang 2008; Palanisamy et al. 2022). However, smelting requires temperatures over 1000 °C, creating a high energetic cost that is partially offset by the burning of plastics (Palanisamy et al. 2022). Furthermore, the gases created from incineration have a negative environmental impact, including generation of CO_2 and dioxins, and can cause negative health impacts (Jirang Cui and Zhang 2008; Dutta et al. 2023; Palanisamy et al. 2022).

4.3.2. Hydrometallurgy

Printed circuit boards, which contain nickel plating, are commonly recycled using hydrometallurgical processes. Hydrometallurgy generally uses a corrosive liquid to leach a solid material. Following leaching, metals are purified through precipitation, extraction, adsorption, and concentration (Jirang Cui and Zhang 2008). Hydrometallurgical processes typically have lower costs, less environmental impact, result in high metal purities, and are simpler to perform in comparison to pyrometallurgy (Jirang Cui and Zhang 2008; Dutta et al. 2023; Palanisamy et al. 2022). Scientifically, they are more predictable and easier to control than high temperature recovery (Jirang Cui and Zhang 2008). Even at suboptimal conditions, 70% of nickel can be recovered (Jirang Cui and Zhang 2008). However, hydrometallurgy may sometimes rely on dangerous reagents (cyanide), use more water, produce more secondary waste, and complicate the combination of several waste streams (Jirang Cui and Zhang 2008; Dutta et al. 2023; Palanisamy et al. 2022).

4.3.3. Bioleaching

Recently bioleaching or biometallurgy has been tested as an alternative for recovering metals from e-waste (Madrigal-Arias et al. 2015; Brandl, Bosshard, and Wegmann 2001; Jirang Cui and Zhang 2008; Dutta et al. 2023; Palanisamy et al. 2022). Bioleaching is considered a more environmentally friendly technology than traditional hydrometallurgy as it involves less energy consumption, has lower operational cost, and can be highly efficient and selective (Madrigal-Arias et al. 2015; Brandl, Bosshard, and Wegmann 2001; Dutta et al. 2023). However, it is limited in its application (Dutta et al. 2023). *Thiobacillus ferrooxidans* and *T. thiooxidans* (extremophilic metal cycling bacteria), and fungi such as *Aspergillus niger* and *Penicillium simplicissimum*, have been shown to mobilize large percentages of transition metals found in e-waste, including nickel (Madrigal-Arias et al. 2015; Brandl, Bosshard, and Wegmann 2001). Brandl et al. have shown up to 80% of nickel can be recovered from e-waste scrap using *Aspergillus niger* (Brandl, Bosshard, and Wegmann 2001). While several reports detail the advantages and effectiveness of bioleaching electronics waste for metal recovery, at the time of writing, there are no known commercial recyclers pursuing bioleaching.

4.4. Platinum Group Metals (PGMs)

PGMs include ruthenium, rhodium, palladium, osmium, iridium, and platinum (US Geological Survey 2023). PGMs, particularly platinum and palladium, are highly sought after due to their wide use in industrial catalysis (Hughes et al. 2021), electronics (Seymour 1985), jewelry (Biggs, Taylor, and van der Lingen 2005), pharmaceuticals (Colacot 2009), and sustainable energy (Katsounaros et al. 2014). Despite the industrial relevance, the US is 66% import reliant for platinum, which costs as much as $980 per troy ounce in 2022 (US Geological Survey 2023). Recycling is crucial to maintain a long-term supply of PGMs. Currently, several PGMs, including platinum, palladium, ruthenium, and rhodium, are successfully recycled from automotive catalysts (Karim and Ting 2021). In fact, 35 tons of rhodium are produced annually and approximately one third of that comes from recycling (Umicore Precious Metals Refining 2023f). Due to their low concentration in e-waste, only 5 to 10% of the PGMs in electronics are recycled (Hagelüken 2012). The majority of PGMs recovered from e-waste are platinum and palladium, due to their use in printed circuit boards.

4.4.1. Pyrometallurgy

Commercial waste recyclers including Noranda, Boliden, and Umicore prefer to utilize pyrometallurgy to recover PGMs (Cayumil et al. 2016). During pyrometallurgy, high temperatures are the main driving forces to separate and purify elements of interest. Pyrolysis processes combine 10 to 15% of e-waste with other feedstocks to recover platinum and palladium in addition to other valuable metals (Cayumil et al. 2016). In this process, waste is usually melted or smelted to first separate and extract copper. The remaining constituents, including PGMs, can be recovered by subsequent leaching or electrorefining, such as electrowinning or electrolytic refining (Cayumil et al. 2016; Bigum, Brogaard, and Christensen 2012; Jirang Cui and Zhang 2008; Dutta et al. 2023). Pyrometallurgy suffers from being inexact, uncontrolled, bears a high energetic cost, and often generates toxic or dangerous gases from the incineration of plastics and halogenated flame retardants present in e-waste (Cayumil et al. 2016; Bigum, Brogaard, and Christensen 2012; Jirang Cui and Zhang 2008; Dutta et al. 2023). However, the process is well understood, allows recovery of several metals including PGMs and transition metals, can combine multiple waste sources including catalytic waste, and recovers metals at high purity (Cayumil et al. 2016; Dutta et al. 2023). Using this process, PGMs can be recovered at up to 99% purity (Cayumil et al. 2016; Jirang Cui and Zhang 2008).

4.4.2. Hydrometallurgy

Hydrometallurgy is an alternative for recovering PGMs being investigated both academically (Cayumil et al. 2016; Jirang Cui and Zhang 2008; Dutta et al. 2023) and by small companies like Mint Innovation (Mint Recycling 2023). Hydrometallurgy requires an aqueous solution to extract metals, rather than the high temperatures used in pyrometallurgy (Cayumil et al. 2016; Dutta et al. 2023). Additionally, in large commercial operations hydrometallurgy is sometimes used to separate and purify metals after initial pyrometallurgical separation (Cayumil et al. 2016; Jirang Cui and Zhang 2008; Dutta et al. 2023). Hydrometallurgy provides more process control, requires less energy, and can recover PGMs at up to 99% purity (Cayumil et al. 2016; Dutta et al. 2023). However, further investigation is required to effectively combine waste streams, reduce generated waste, and require less expensive or exotic reagents (Cayumil et al. 2016; Dutta et al. 2023).

4.4.3. Biometallurgy

Bioleaching has been commercially utilized for the recovery of copper from copper ores since the 1980s (Olson, Brierley, and Brierley 2003; Dutta et al. 2023). Both Faramazi et al. (Faramarzi et al. 2004) and Brandl et al. (Brandl, Bosshard, and Wegmann 2001) have shown gold and transition metals can feasibly be recovered from printed circuit boards using bioleaching. Though PGMs have not been specifically targeted in printed circuit boards, others have shown bioleaching effective for platinum recovery from automotive catalysts (Yakoumis et al. 2021). At the time of writing, there are no commercial operations for biometallurgical recovery of PGMs from e-waste.

4.5. Tantalum

Tantalum is an essential metal for use in consumer electronics, particularly of use in capacitors. 20% of the global tantalum supply comes from recycling or synthetic concentrates (Klaus J. Schulz 2017). However, tantalum is extremely scarce and not often recovered from consumer products because it is present in such small quantities. The US is 100% import reliant for tantalum as it has not been produced domestically in over 60 years (US Geological Survey 2023; Klaus J. Schulz 2017). Effective tantalum recycling is necessary to support the domestic supply needs and, specifically, the electronics industry. Several methods have been developed to facilitate tantalum recycling at both bench and industrial scales, described in detail below.

4.5.1. Pyrometallurgy

Pyrometallurgy utilizes high temperature treatment wherein capacitors are mechanically separated and then treated at high temperatures to collapse silica and leave behind the tantalum anode (Agrawal et al. 2021). A further heat treatment is used to recover tantalum metal as fine powder. Though still profitable, the energy cost for this process is very large, a considerable amount of tantalum may be lost as tantalum oxide, and the final product requires further processing to achieve the desired tantalum grade (Römer, Elwert, and Goldmann 2016; Agrawal et al. 2021). However, several companies utilize this method to recycle tantalum, including Umicore (Umicore Precious Metals Refining 2023h), Quest Metals (QuestMetals 2023), and Oryx Metals (OryxMetals 2019). Vacuum pyrolysis can be combined with pyrometallurgy to facilitate a faster reaction at a lower temperature. Using vacuum pyrolysis, 98% of tantalum oxide can be recovered with 99% purity (Z. Chen et al. 2018).

4.5.2. Hydrometallurgy

Hydrometallurgy, which includes separation and purification through leaching, is effective as a secondary treatment in tantalum recycling. High temperature oxidation followed by hydrometallurgy involves two steps. High temperature oxidation removes resin from the capacitor, leaving behind tantalum oxide, followed by recovery of metallic tantalum (Agrawal et al. 2021). By extending these steps to include magnetic separation, sieving, pulverizing, and acid leaching 98.6% pure tantalum can be recovered (Mineta and Okabe 2005).

While high temperature oxidation is effective for removing the mold resin, high temperatures may cause destruction of the tantalum electrode, making it impossible to separate from silica in the capacitor (Mineta and Okabe 2005; Agrawal et al. 2021). Alternatively, it has been shown that the components of the capacitor can all be dissolved in ionic liquids, leaving the tantalum anode (Spitczok von Brisinski, Goldmann, and Endres 2014). A mixture of Lewis acidic and basic ionic liquids has been shown to be the most successful, including dialkylimidazolium, halides, and $AlCl_3$ (Agrawal et al. 2021; Spitczok von Brisinski, Goldmann, and Endres 2014). Currently, task specific ionic liquids (TSILs) are being developed to more efficiently address tantalum recycling (Micheau et al. 2020; Turgis et al. 2018; Micheau et al. 2019).

4.5.3. Pyrolysis

Pyrolysis is also an effective and popular method for tantalum recycling. Here the mold resin is decomposed, and products are collected as oil, gas, and solid residue (Agrawal et al. 2021). The solid residue is then crushed and magnetically separated. Finally, tantalum oxide powder is recovered through chlorination (Agrawal et al. 2021; Niu, Chen, and Xu 2017a). Pyrolysis is widely considered to be more effective and energy efficient than comparable pyro or hydrometallurgical techniques. Under optimal conditions pyrolysis can reach a recovery efficiency of 98% and obtain a product of 99.9% purity (W.-S. Chen, Ho, and Lin 2019).

4.5.4. Steam Gasification

Steam gasification involves recovering tantalum oxide by heating capacitors with steam and sodium hydroxide. The capacitor is heated for 5 minutes and then cooled, while the injection of heated sodium hydroxide allows the components of the capacitor to be dissolved in distilled water (Katano, Wajima, and Nakagome 2014). A tantalum compact can then be recovered after filtration and sieving. Steam gasification requires a lower reaction temperature and pressure, less expensive reactants, and traps halogen gases that are generated (Agrawal et al. 2021;

Katano, Wajima, and Nakagome 2014). To date this recovery process has only been explored at laboratory scale.

4.5.5. Supercritical Water

Supercritical water treatment has also been recently developed for the recovery of tantalum. Supercritical oxidation and supercritical depolymerization can be facilitated by treating capacitors in supercritical water in the presence of an oxidant or reductant, respectively (Wang, Chen, and Xu 2015; Gong et al. 2016). Following oxidation, the resulting powder is washed and collected as a tantalum electrode. Depolymerization requires further mechanical separation to produce tantalum particles. Organic decomposition of the resin is facilitated at a higher rate using oxidation, decomposing 100% of the organic phase, while depolymerization is limited to 70% decomposition (Niu, Chen, and Xu 2017b; Wang, Chen, and Xu 2015; Gong et al. 2016). At the time of writing, supercritical water treatment has been limited to the laboratory scale.

4.6. Titanium

Currently, titanium does not appear to be recovered from small consumer electronics in significant quantities. This lack of interest in recovery is likely due to a combination of two factors: low concentration in electronics, and low market price of titanium. Despite being a CM (United States Geological Survey (USGS) 2022) on which the US is over 95% import reliant (US Geological Survey 2023), titanium only had a market value of $11 per kilogram in 2022 (Table 1-1 (US Geological Survey 2023)). In small consumer electronics, titanium is present in low concentrations (0.1332 w/w% in cell phones (Buechler et al. 2020)), and it is relatively dispersed. Typically, it is found in the form of barium titanate in acoustic devices, though it may also be used as a barrier coating in integrated circuits (Christian et al. 2014). Compared to a metal such as tin, which is present in higher concentrations (approximately 3 w/w% in cell phones (Buechler et al. 2020)) and has a market value of $35 per kilogram (Table 1-1 (US Geological Survey 2023)), titanium is not currently economically appealing to recover.

Specialized devices in which titanium is present in higher concentrations, such as MRI magnets (37 w/w% (RINA Consulting Ltd. 2019)), tend to have lifetimes greater than 10 years, so the waste generated from these sources is limited (Takeda, Ouchi, and Okabe 2020). However, some small-scale operations are targeting these devices. For instance, OrthoMetals, a company based in the Netherlands, works with over 1,300 crematoria worldwide to recycle metals that remain after cremation, including titanium (OrthoMetals 2023). Their facility separates metals by composition and sells them to smelters, which use them for automotive or additive applications (OrthoMetals 2023).

4.7. Tin and Indium

E-waste is the largest potential source for recycled tin, as 44.1% (C. Yang, Tan, et al. 2017) of refined tin consumed worldwide each year is used for solder in electronics (International Tin Association 2023). Naturally, a variety of techniques have been explored for tin extraction from e-waste, including hydrometallurgy (Moosakazemi, Ghassa, and Mohammadi 2019), pyrometallurgy (Hossain et al. 2019), biometallurgy (Jiaying Cui et al. 2021), electrowinning (T. Yang, Zhu, et al. 2017; Peres, Pereira, and Martins 2012), and combinations thereof. Qualitatively, most studies on tin recovery from e-waste appear to focus on printed circuit boards/printed wiring boards (Moosakazemi, Ghassa, and Mohammadi 2019; T. Yang, Zhu, et al. 2017; Hossain et al. 2019; Peres, Pereira, and Martins 2012; Havlik et al. 2010; Y. Chen et al. 2021), which use tin-based solder to fasten electronic components to their surfaces (C. Yang, Tan, et al. 2017) and are approximately 4% tin by weight (Huang, Guo, and Xu 2009).

The majority of these studies are performed at the laboratory scale, but tin has been recycled from e-waste on larger scales. For instance, Mitsubishi Materials Corporation (Mitsubishi Materials Corporation 2023) and Umicore (Umicore Precious Metals Refining 2023a, 2023e) both smelt and refine at least 100,000 tons per year (Itronics Inc. 2020) of printed circuit boards. Both operations recover tin, along with other metals, through pyrometallurgy-based processes (Hsu et al. 2019; Mitsubishi Materials Corporation 2023). Because its economic value is lower than that of other metals commonly found in e-waste (US Geological Survey 2023), tin is generally a lower priority for recovery than metals such as palladium (C. Yang, Tan, et al. 2017). However, an increase in commercial tin recycling is needed to ensure future demand is met; at current production and consumption rates, world reserves of tin will be depleted in roughly 10 years (C. Yang, Tan, et al. 2017).

Indium is often found with tin in e-waste in the form of indium tin oxide (ITO); in fact, the majority (55-85%) of indium produced worldwide is consumed for ITO production (Gu, Summers, and Hall 2019). Indium recovery from e-waste is challenging because 1) it is highly dispersed in electronics and 2) electronics are not designed with indium recycling in mind (Forti V. 2020). Additionally, the e-waste recycling industry generally lacks sufficient indium extraction technology (Swain and Lee 2019). However, the US is 100% import reliant on indium (US Geological Survey 2023), 18% of which is imported from China (US Geological Survey 2023). Due to reliance on a non-allied country for supplies, indium recovery from secondary sources is worth exploring.

4.7.1. Pyrometallurgy, Biometallurgy and Hydrometallurgy

Techniques studied in the literature for indium recovery for e-waste include pyrometallurgy (He, Ma, and Xu 2014), biometallurgy (Jowkar et al. 2018), and hydrometallurgy (K. Zhang et al. 2017). Most studies on indium recovery from flat panel displays, the primary use for ITO (US Geological Survey 2023), are still only at a laboratory scale (Fontana et al. 2021). However, a few large-scale facilities are currently in operation. For instance, the Industrial Technology Research Institute (ITRI) operates a pilot plant in Taiwan which treats 3 tons of LCD panel waste per day, resulting in 750 g of indium (Industrial Technology Research Institute 2023; European Association of Research and Technology Organisations (EARTO) 2023). Additionally, Umicore can recover indium from a variety of e-waste fractions with its blast furnace, but the facility can only process 50 tonnes of indium-containing products each year (Umicore Precious Metals Refining 2023g, 2023b). Overall, indium is rarely recovered from EOL applications because doing so is more expensive than primary production costs (Ciacci et al. 2019). For instance, it is estimated to cost $3451 to obtain 1 kilogram of indium from recycled CIGS solar modules (Redlinger, Eggert, and Woodhouse 2015), whereas the price of indium metal obtained from ore is around $250 per kilogram (2023). A significant decrease in recycling costs will be necessary to make indium extraction from e-waste economically viable.

4.8. Tungsten

Tungsten is widely used in alloys, carbides, steels, and electronics (US Geological Survey 2023). No domestic production of tungsten currently exists in the US; however, several companies can convert tungsten reagents to tungsten metal powder necessary for commercial applications (US Geological Survey 2023). As a result, the US is more than 50% import reliant for tungsten starting materials, with the majority being imported from China (US Geological Survey 2023). Presently, tungsten is often recycled from tungsten alloy scrap and carbide scrap

(Umicore Precious Metals Refining 2023i). Despite their inclusion in capacitors, lamps, phones, tungsten is not currently recycled from electronics due to low concentrations (Zeiler, Bartl, and Schubert 2021).

Currently, it is not considered economically viable to recover low concentrations of tungsten from electronics, but it may be possible in the future if tungsten components can be disassembled with lower labor costs (Reck and Graedel 2012; Zeiler, Bartl, and Schubert 2021). Tungsten is recycled from other applications through direct and indirect recycling processes (Shemi et al. 2018). Direct methods take supplied material and transform it into tungsten powder of interest by high temperature reaction in molten zinc (Barnard and Kenworthy 1969; Shemi et al. 2018). This method is considered the most cost-efficient and environmentally friendly method; however, it is not applicable for e-waste that has not been disassembled and sorted (Barnard and Kenworthy 1969; Shemi et al. 2018). Indirect methods are those that convert tungsten carbide scrap to an intermediate compound and then further process them to create tungsten metal.

4.9. Rare Earth Elements (REEs)

4.9.1. Pyrometallurgical Techniques

Despite being used in several (Tabelin et al. 2021) e-waste recycling operations worldwide to recover other metals, such as PGMs (Umicore Precious Metals Refining 2023g), pyrometallurgy is generally not used for REE recovery on an industrial scale. For reference, Umicore does not appear to recover REEs, though it extracts other CMs from printed circuit boards, computers, cell phones, and more with its smelters (Umicore Precious Metals Refining 2023e). This is likely because pyrometallurgy is most suitable for sources with relatively high concentrations of target metals (Sun et al. 2017).

4.9.2. Hydrometallurgical Techniques

Although the literature reports high (77 to 100% (Ramprasad et al. 2022)) REE recovery for various hydrometallurgical methods on laboratory scales, hydrometallurgy has not been used for REE recovery from e-waste on an industrial scale. This discrepancy is likely due to difficulty in scaling e-waste recycling processes, which may have a number of potential root causes.

Pilot plants for REE recovery from specific e-waste categories, such as NiMH batteries (Yuksekdag et al. 2022), waste phosphors (Yuksekdag et al. 2022), and magnets (REEcycle 2021a) have been constructed. REEcycle, a start-up focused on metal recovery from magnets, claims its process can recycle MRI magnets with a 99.8% recovery efficiency for REEs (REEcycle 2021b). The process consists of mechanical abrasion, crushing, leaching with a proprietary solvent, and gravity filtration (REEcycle 2021a). The project has received both Phase I and Phase II funding from the National Science Foundation and has moved forward with the building of a demonstration facility (REEcycle 2021c), though the current status of the project is unclear. In general, further studies are needed to better understand the performance, environmental impact, and cost of hydrometallurgical REE recovery processes on large scales (Ramprasad et al. 2022).

4.9.3. Alternative Techniques

A variety of alternative (i.e., non-pyro- and hydrometallurgical) methods have also been tested for REE recovery from e-waste. These methods have generally been explored on smaller scales than traditional methods, but they tend to be touted as more environmentally friendly. Most of these methods can be classified into one or more of the following broad categories: magnet-to-magnet, biometallurgical, electrochemical, supercritical, cryogenic, and nanomaterial-based methods.

4.9.3.1. Magnet-to-Magnet Techniques

A company in Texas, Noveon Magnetics, Inc. (formerly known as Urban Mining Company), recycles roughly 2000 tons per year of NdFeB magnets (Braeton J. Smith et al. 2022; Zakotnik et al. 2016). By combining scrap NdFeB magnets with new REEs, Noveon is able to synthesize new magnets with the necessary magnetic properties to be used in several different applications. To do this, Noveon removes additives from scrap NdFeB magnets both mechanically and using nitric acid. After that, scrap REEs are combined with fresh starting materials and undergoes a high-temperature hydrogenation process to produce starting material for new magnets [49, 50]. While this allows up to 90% recovery of waste rare earths, magnet-to-magnet recycling still requires the use of virgin rare-earth materials and does not recover rare-earths for use outside of magnet production.

4.9.3.2. Biometallurgical Techniques

Based on a systematic review (Brown et al. 2023) of publications from 2000 to 2020, interest in biometallurgy for REE recovery from e-waste has significantly increased since 2014. This growth can be attributed to the fact that, compared to traditional methods, biological techniques are relatively eco-friendly. For instance, they consume less energy (Dutta et al. 2023) and produce less hazardous waste (Brown et al. 2023) than pyro- and hydrometallurgy. Additionally, biometallurgical techniques are already well established for other metals – copper bioleaching has been performed commercially since the 1950s (Brierley and Brierley 2001) – so it is possible that existing systems could be adapted to REEs.

Though a handful of studies (Beolchini et al. 2012; Reed et al. 2016; Auerbach et al. 2019) have shown biological methods to be promising for REE recovery from urban (including electronic) wastes at the laboratory scale, these methods have yet to be implemented commercially. Most recent studies on bioleaching of REEs from e-waste only demonstrate technological readiness levels (TRLs, Figure 4-3) less than or equal to 4 (Brown et al. 2023; Magrini and Jagodzińska 2022), and at the time of writing, there do not appear to be any TRL = 5 REE bioleaching or biosorption plants in the US (Brown et al. 2023). Thus, further research at higher TRL scales is needed to expand fundamental knowledge on biological methods for REE recovery, validate them for industrial use, and increase their TRLs (Brown et al. 2023; Rene et al. 2021).

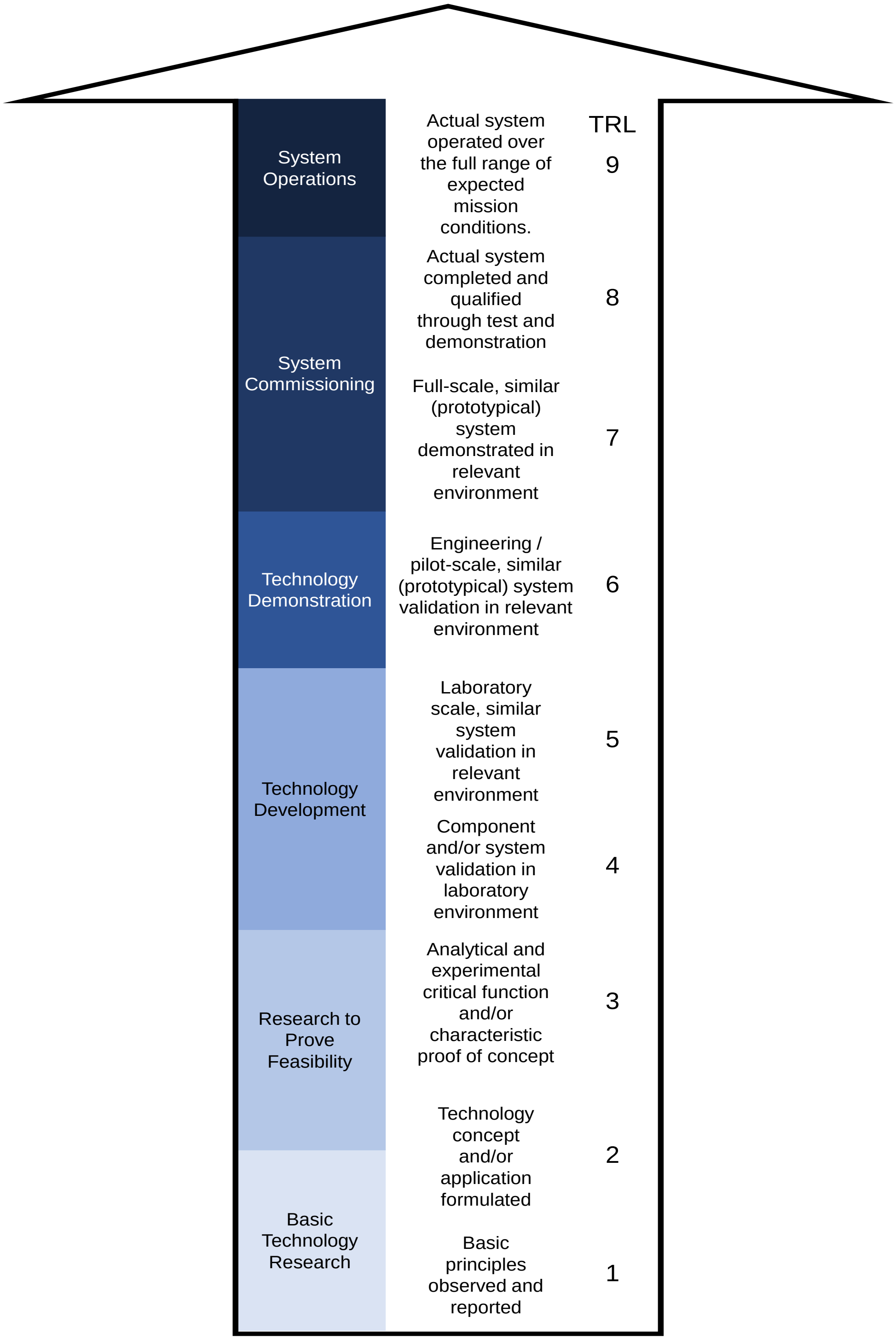

Figure 4-3: Schematic of Department of Energy Technology Readiness Levels [Figure adapted from (US Department of Energy 2011)].

4.9.3.3. Electrochemical Techniques

ECs investigated for REE recovery from e-waste include electrodeposition, electrosorption, and electrocoagulation (Ramprasad et al. 2022). Much of the literature for ECs focuses on NdFeB permanent magnets (Makarova, Soboleva, et al. 2020; Makarova, Ryl, et al. 2020), which are less complex in composition compared to other fractions of e-waste. Unlike biometallurgical techniques, ECs are being explored on larger scales; for instance, SANTOKU Corporation operates a plant in Japan that recycles Nd and Dy from EOL magnets via molten salt electrolysis (Mudali et al. 2021). It is relevant to note that while molten salt electrolysis is the industry standard for REE metal conversion (Abbasalizadeh et al. 2017), this EC is not preferable due to the hazards associated with high (427–870 °C (Pérez-Cardona et al. 2022)) temperature molten halides. At the time of writing, ECs do not appear to be used for REE recovery for other types of e-waste beyond the laboratory scale.

4.9.3.4. Supercritical Techniques

Supercritical CO_2 has proven to be effective for REE recovery from fluorescent lamps (Y and Eu) (Shimizu et al. 2005) and NdFeB magnets (Nd, Pr, and Dy) (J. Zhang et al. 2018) on a laboratory scale. However, large-scale studies are limited, and at the time of writing, supercritical fluids (SCFs) do not appear to be used to recover REEs from e-waste on an industrial scale.

4.9.3.5. Cryogenic Processes

Cryo-milling, a process in which solids are broken into nano-sized particles at very low temperatures (Ambaye et al. 2020), has been reported (Tiwary et al. 2017; Sharma et al. 2020) as a pretreatment step for metal recovery from e-waste. This technique has not been investigated specifically for REE extraction, but it could be implemented in a multi-step REE recovery process, since it is effectively just the freezing and subsequent size reduction of waste (Castro and Bassin 2022). Cryo-milling processes are known to result in high metal recovery rates (100% of metals in printed circuit boards (Tiwary et al. 2017)) due to their ability to process e-waste into fully separable constituents (Tiwary et al. 2017). Compared to hydrometallurgical methods, though, they consume more energy (Tiwary et al. 2017; Ambaye et al. 2020). However, in general, literature on cryogenic methods is scarcer than for other methods. Further research is needed to understand the scalability and economic viability of cryogenic methods for REE recovery from e-waste.

4.9.3.6. Nanomaterial-based Processes

Carbon-based nanomaterials have been proposed (Cardoso et al. 2019) for REE recovery from e-waste via solid phase extraction. These materials are of interest because they are relatively environmentally friendly and can be tuned via the addition of functional groups to enhance their effectiveness (Ambaye et al. 2020). However, the majority of the literature on graphene oxide composites and carbon nanotubes only explores mono-elemental REE solutions with no competing ions (Cardoso et al. 2019). At the time of writing, these materials do not appear to have been tested on real e-waste streams. Testing of carbon-based nanomaterials with complex, multi-elemental solutions is the first step needed to assess whether these materials are viable for REE recovery from real e-waste streams.

4.9.3.7. Other Techniques

Though the above categories cover the majority of alternative REE recovery methods, they are not exhaustive. Other notable techniques being explored in the literature include flash Joule heating (FJH) (Deng et al. 2021) and selective sulfidation (Stinn and Allanore 2022). FJH, a technique in which metals are evaporated from e-waste at high (approximately 3400 K (Deng et al. 2021)) temperatures, may consume 80 to 100 times less energy than traditional pyrometallurgical techniques (Deng et al. 2021). When tested on printed circuit boards, this method demonstrated recovery yields greater than 80% for precious metals such as rhodium and palladium (Deng et al. 2021). FJH is currently being scaled-up for the production of graphene (Universal Matter 2023), but it has not progressed beyond the laboratory scale for e-waste processing.

Selective sulfidation is a technique in which a target metal (M) in the form M-X (where X is typically oxygen) undergoes an anion exchange reaction to form M-Y, where Y is sulfur (Stinn and Allanore 2022). This method is of interest for e-waste processing because it allows for the facile separation of mixed oxides, as sulfide and oxide particles differ enough in size that they may be separated by physical means (Stinn and Allanore 2022). Achieving improved separation of waste in the solid phase reduces the volume of solvent required in later liquid-liquid extraction stages (Stinn and Allanore 2022). Compared to the hydrometallurgical processing of bastnaesite, selective sulfidation is projected to save on capital costs while reducing greenhouse gas emissions by 60 to 90% (Stinn and Allanore 2022). Although it has been investigated on a laboratory scale for rare-earth magnets and found to be 100 times more effective than state-of-the-art hydrometallurgy at separating dysprosium from neodymium and praseodymium (Stinn and Allanore 2022), at the time of writing, selective sulfidation does not appear to have been scaled-up for e-waste processing.

4.10. Patent Search

A patent search was performed using the database Patsnap to further investigate the intellectual property landscape for CM recovery from e-waste. A selection of key words – primarily, CM names and synonyms/variations of “extract” and “electronic waste” – was searched to obtain the initial results. These results were sorted by CM, manually reviewed to remove irrelevant patents, and then inspected for a refined set of key words/phrases to identify technology gaps specific to the 32 CMs. Figure 4-4 summarizes the results of this search. As shown in Figure 4-4, tin (Sn), palladium (Pd), aluminum (Al), nickel (Ni), platinum (Pt), and indium (In) were the six critical materials that returned the most patents. Except for indium, “circuit board” was the keyword/phrase that appeared most frequently for these materials. Other keyword/phrases that appeared frequently were “catalyst,” “capacitor,” and “indium tin oxide” or “ITO.” For tin, the word “solder” appeared in 32% of the returned patents, and for indium, the words “liquid crystal” or “LCD” appeared in 47%.

More detailed patent search results, along with a description of the search procedure, are provided in Appendix A.

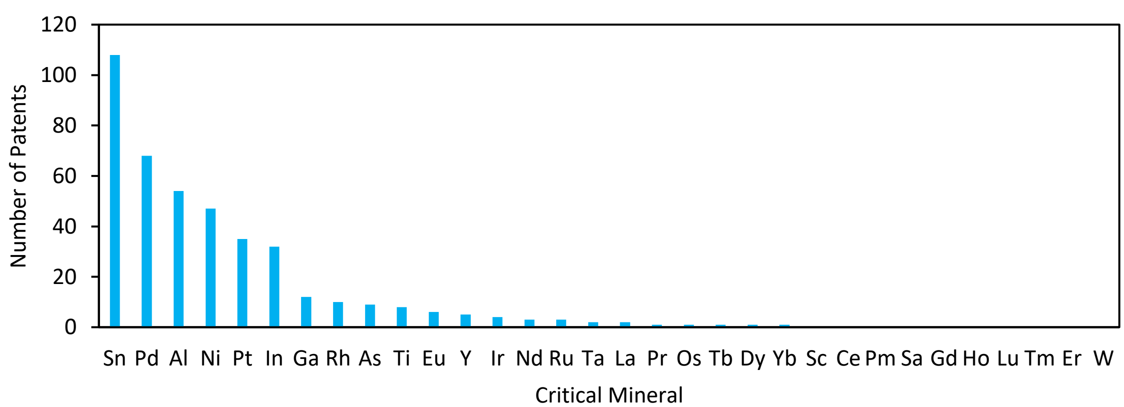

Figure 4-4: Number of patents returned for each critical material.

4.11. Summary

This chapter explores current recovery efforts and technological advancements for a selection of CMs. Table 4-1 shows the status of each CM and their respective recovery technologies.

Table 4-1: Summary of CM recovery technologies from e-waste

Critical Material (CMs)	Are technologies being applied for recovery from e-waste?	Comments
Aluminum (Al)	No	Remelting and refining technologies are being used to recover aluminum from cans and other products. It is not clear if aluminum is being recovered from e-waste.
Arsenic (As)	No	No arsenic is being recovered from e-waste, but vacuum pyrolysis and hydrometallurgical techniques are being investigated for bench scale recovery.
Gallium (Ga)	No	Gallium is not being recycled from e-waste. Gallium is primarily recovered from new scrap generated during manufacturing. Vacuum pyrolysis and hydrometallurgical techniques are being investigated for bench scale recovery.
Nickel (Ni)	Yes	Nickel is primarily recovered from nickel containing battery cathodes. It is unclear how much nickel is recovered from other e-waste such as printed circuit boards.
Platinum Group Metals (PGMs)	Yes	The majority of PGMs are recycled from catalytic applications. It is estimated that 5-10% of PGMs in e-waste are recycled using pyrometallurgical or hydrometallurgical techniques.
Tantalum (Ta)	Yes	Tantalum is recovered from e-waste, primarily from printed circuit boards and capacitors, using pyrometallurgical and hydrometallurgical techniques.
Tungsten (W)	No	Tungsten is not currently recovered from e-waste. Though it could be recovered, it is widely considered uneconomical due to its low concentration.
Titanium (Ti)	No	Titanium does not currently appear to be recovered from e-waste; this is presumably due to its low concentration and market price.
Tin (Sn)	Yes	Tin is currently recovered from e-waste – primarily printed circuit boards - on an industrial scale using pyrometallurgical processes.
Indium (In)	Yes	Indium is currently recovered from a variety of e-waste fractions on the pilot scale using a combination of pyro- and hydrometallurgical techniques.
Rare Earth Elements (REEs)	Yes	Several techniques have been explored for REE recovery from e-waste on a laboratory scale, but only a few (i.e., hydrometallurgical, electrochemical, and magnet-to-magnet) have been implemented on the pilot scale or larger.

5.0 Gap Analysis

5.1. Introduction

As previously discussed, the refined list of the 32 CMs which are most relevant to e-waste was developed. The list, which consists of aluminum, arsenic, gallium, indium, nickel, tantalum, tungsten, titanium, tin, PGMs (platinum, palladium, rhodium, ruthenium, osmium, and iridium), and REEs (lanthanum, cerium, praseodymium, neodymium, promethium, samarium, europium, gadolinium, terbium, dysprosium, holmium, erbium, thulium, ytterbium, lutetium, scandium, and yttrium), was established by considering a variety of criteria, including:

- Availability
- Market demand and price
- Typical concentration in devices and/or number of devices in which the CM is found
- Import reliance

The selected 32 CMs were explored in further detail in Chapter 4, which examines the current state of their recovery from e-waste. Table 5-1 summarizes the findings of Chapter 4 by illustrating the major CM recovery technologies along with information about their scale of application for individual CMs.

Table 5-1: Critical materials recovery technologies.

Critical Material (CMs)	Pyro metallurgical	Hydro metallurgical	Bio metallurgical	Electrochemical	Supercritical Fluid (SCF) Extraction	Vacuum Metallurgical	Remelting / Refining
Aluminum (Al)							[orange]
Arsenic (As)		[grey]				[grey]	
Gallium (Ga)		[grey]				[grey]	
Nickel (Ni)	[orange] *	[orange]	[grey]				
Platinum Group Metals (PGMs)	[orange] *	[orange]	[grey]				
Tantalum (Ta)	[orange] *	[orange]	[grey]	[grey]	[grey]	[grey]	
Tungsten (W)	[grey]						
Titanium (Ti)	[orange]						
Tin (Sn)	[orange] *	[grey]	[grey]	[grey]			
Indium (In)	[orange] *	[orange] *	[grey]				
Rare Earth Elements (REEs)	[grey]	[orange] *	[grey]	[orange] *	[grey]		

*Notes: Grey shading = technology present at bench/laboratory scale. Orange shading = technology present at pilot scale or higher. No shading = no information found. The symbol * denotes the existence of pilot scale or larger operations that are specifically processing e-waste streams. Below are the details of the CMs that are being recovered using pilot or larger operations.*

**Ni- Nickel is being recovered from EOL battery electrodes by large industrial recyclers such as Umicore. Umicore does not share its process for recycling batteries. Nickel is also present in printed circuit boards, though it is unclear if it is being recycled from other e-waste streams.*

PGM – 5 to 10% of PGMs in e-waste are estimated to be recycled. Industrial recyclers such as Umicore incorporate platinum into their pyrometallurgical processes, while smaller companies like Mint Recycling are utilizing hydrometallurgical processes.

REEs - REEcycle has recovered REEs from EOL magnets using hydrometallurgy in a pilot facility in Texas, though it is unclear if the facility is still in operation. SANTOKU Corporation currently recovers REEs from EOL magnets in an industrial-scale operation in Japan using molten salt electrolysis.

Indium - The Industrial Technology Research Institute (ITRI) operates a pilot plant for indium recovery from LCD panel waste. Umicore can process 50 tonnes per year of indium-containing waste with its furnaces.

Tin - Mitsubishi Materials Corporation and Umicore both smelt and refine at least 100,000 tons per year of printed circuit boards, from which tin and other metals are recovered.

Tantalum – Umicore recovers tantalum from wire scrap, EOL capacitors and used sputtering targets. Additionally, Oryx Metals will buy tantalum materials for recycling, focusing on scrap.

5.2. Gaps in Patents

Based on the results of the patent search discussed in Chapter 4 (4.10), tin, palladium, aluminum, nickel, platinum, and indium are relatively well explored in terms of intellectual property for recovery from e-waste. For all other CMs, there was a distinct lack of patents. It was concluded that the current intellectual property for CM recovery from e-waste generally focuses on specific components that contain high concentrations of high-value materials. The patent search determined that there is a distinct need for technologies that can recover the following CMs: titanium, REE, tantalum, gallium, and arsenic.

5.3. Specific Gaps in CM Technologies

Overall, there is a lack of directly scaled and/or applicable technology for recovering CMs from e-waste. However, there is ongoing work in this area, which is demonstrated by early-stage research in literature. Industrial pyrometallurgical processes developed by Noranda, Rönnskar, and Umicore recover PGMs, nickel, and tantalum from e-waste by incorporating it in their traditional smelting process. Umicore also recovers indium and tin, and companies such as Noveon Magnetics, Inc. and SANTOKU Corporation have established pilot plants for REE recovery from waste magnets. The following subsections briefly detail specific gaps for the selected 32 CMs.

5.3.1. Aluminum

Aluminum has an established recycling process; 75% of the aluminum globally produced is still in use. However, the extent to which aluminum is being recycled from e-waste is unclear. Though a handful of companies claim to be extracting aluminum from e-waste products such as phones and solar panels, it appears that mostly cans and building materials are recycled. There is a need to understand tolerance for utilizing the secondary aluminum from e-waste specifically.

5.3.2. Gallium and Arsenic

Both gallium and arsenic have not been produced in the US since 1980. Gallium and arsenic are both pivotal for use in semiconductor wafers for integrated circuits. Gallium also finds use in optoelectronics including LEDs and solar cells, while arsenic is combined with indium and aluminum in other semiconductors. While gallium may be replaced in optoelectronics applications, there are no effective alternatives for digital GaAs-based integrated circuits.

There are no commercial processes for recycling gallium or arsenic from GaAs-based semiconductor wafers. Technology currently focuses on recovering gallium or arsenic from production waste generated during semiconductor manufacturing. This gap exists for two reasons. First, gallium and arsenic are both difficult to work with. Gallium’s disparate nature makes it hard to recover in high quantities, while arsenic’s toxicity raises safety concerns. Additionally, the resins and plastics included in GaAs semiconductors complicate the separation of gallium and arsenic from the system.

5.3.3. Nickel

Nickel has scaled recycling industries for sources other than e-waste using traditional smelting, but there is room for improvement of the technology and for specific applicability to e-waste. More targeted techniques can be used while reducing the environmental impact. Currently, nickel is being recovered using pyrometallurgical technologies from batteries on an industrial scale.

5.3.4. Platinum Group Metals

PGMs are found among several industrially relevant applications, including in several electronics. However, the majority of PGMs are found in the catalysis industry, most frequently as automotive catalysts, which most recycling technologies are catered towards. While there are techniques that focus on the retrieval of PGMs from waste electronics, only a very small percentage of PGMs are recovered from e-waste. There is a dearth of technologies and investment for the recovery of PGMs from e-waste.

5.3.5. Tungsten

Small amounts of tungsten are found in e-waste, particularly in phones and other devices that require speakers and microphones. Since tungsten makes up such a small weight percentage of e-waste, it is not currently considered economically viable to recover it. While some laboratory-scale techniques exist to recover tungsten, there is a gap in commercial implementation due to economics.

5.3.6. Titanium

Due to its low concentration in most e-waste and a lack of suitable recovery technologies, titanium is not currently economically appealing to recover. There is a need to identify cost-effective methods for titanium extraction.

5.3.7. Tin

Tin is already being extracted from EOL electronics on an industrial scale. However, because e-waste is the largest potential source for recycled tin, an increase in commercial tin recycling is needed to ensure future demand is met. Current recovery efforts seem to focus on the solder in printed circuit boards, so further research on efficient extraction methods for other forms of tin (e.g., indium tin oxide) should be conducted.

5.3.8. Indium

Currently, the US is 100% import reliant for indium. However, recovering indium from EOL applications such as solar panels is more expensive than primary production from ores. A significant decrease in recycling costs is necessary to make indium extraction economically viable.

5.3.9. Rare Earth Elements (REE)

REEs are essential for a variety of defense technologies, including satellite communications and guidance systems. Though a variety of methods have been explored for their extraction on bench/laboratory scales, further technological development at higher TRLs (i.e., pilot plants or larger) is needed to expand REE recovery and validate the use of these techniques on an industrial scale. In particular, it would be beneficial to investigate "alternative" methods such as biometallurgy, which is already established commercially for other metals and is relatively environmentally friendly in comparison to traditional pyro- and hydrometallurgy.

5.4. Specific Gaps in Recycling Infrastructure

Knowledge about supply chains and life cycles of electronic items is essential to promote circularity in e-waste. The current EOL e-waste management system focuses on disposal rather than improving methods for creating or adding value from e-waste. This is partly due to a lack of well-defined infrastructure and a lack of awareness in the value proposition of e-waste. The various segments of recycling infrastructure such as transportation, collection centers, sorting systems, and recyclers lack connectivity as shown in Figure 5-1. The infrastructure needs clear routing mechanisms for e-waste from consumers to recyclers. Manufacturers, distributors, consumers, and recyclers appear partially unaware of the valuable resources in e-waste. Circular strategies R0 through R9 described in Chapter 2 are not currently being implemented effectively due to this lack of understanding. Quantifying and communicating the value of e-waste are vital to the recovery of CM. Additional information on the geographical location of the e-waste, logistics of transportation and collection of the e-waste, are other key aspects to the capture and recovery of CM.

Overall, adopting principles from the 10 circular strategies is needed (see Table 2-1). Specifically, improved sorting and screening technologies would greatly benefit recycling efforts. Further, implementing extended producer responsibility (EPR) or similar responsibility driven e-waste management techniques will promote capturing valuable CMs from e-waste.

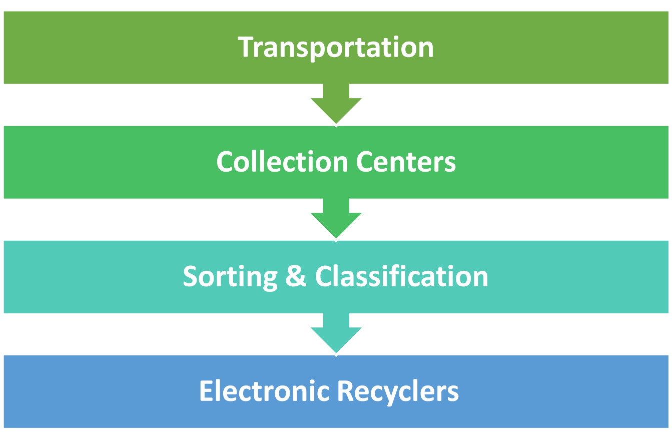

Figure 5-1: Recycling infrastructure.

As mentioned in Section 5.3, there is a need for technology innovation in CM recovery from e-waste, providing opportunities in several areas (Figure 5-2). Improvements in fast screening, sorting, and classifying e-waste would help in efficiently processing e-waste during EOL management. Better product design with a focus on modularity and recovery strategies in mind can help extend product lifetime and easy implementation of the R10 concepts. Additionally, products made from recycled materials can aid in a circular economy.

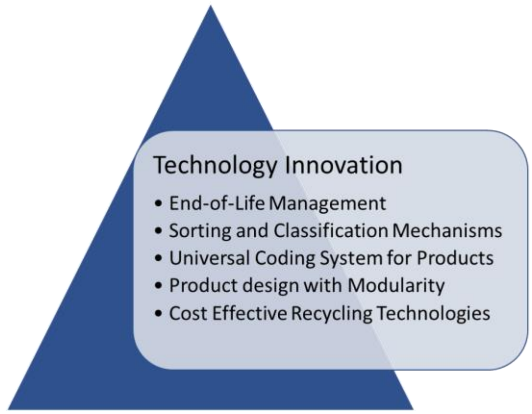

Figure 5-2: Technology gaps.

Regulations and legislation can play a significant role in e-waste management. Spreading awareness on the intrinsic value and the potential downsides of landfilling e-waste amongst citizens and stakeholders can ensure maximum participation and accountability. Creating incentives for implementation of circular economy strategies can improve circularity of e-waste.

5.5. Summary

Successful e-waste management will typically cover all stages of supply chain flow in the recycling process. Scaling cost-effective recycling technologies for recovering CM from e-waste is one of the biggest needs identified through the research in this report. Technologies such as hydrometallurgy and pyrometallurgy are not ideal to recover multiple low volume fraction elements typically found in e-waste. Hence, novel cost-effective technologies to recover low volume fraction elements such as tantalum in e-waste are required. Specifically, the patent search illustrated a need for technologies that can recover the following CMs: titanium, REE, tantalum, gallium, and arsenic. Additionally, government regulations and incentives, manufacturer responsibilities, market demand for materials, consumer behavior, and connections between supply chain segments (e.g., connecting recyclers and material end users) all play an important role in creating a successful circular economy for e-waste. An increased understanding of connections between recovered materials and manufacturing processes will aid in circularity of materials in the marketplace. Further research is also required to address the human health, social and environmental justice outcomes of developing CM recovery recycling technologies.

6.0 Recommendations

6.1. Summary

Recycling of e-waste is critical to the recovery of CMs and waste treatment. As discussed in Chapter 1, the value distribution for different electronic scrap samples shows that a diverse range of CMs is found in solar panels, wind turbines, CRT screens, LED/LCD screens, computers, EV magnets and medical devices. A study (Althaf, Babbitt, and Chen 2021) indicated that the amount of CMs in e-waste generated in the US is more than the amount of CMs consumed for manufacturing new electronic products. Hence, there is a significant value proposition and an economic opportunity in recycling e-waste.

This report explores the various metal recovery technologies and presents the current state of the recycling technology for the CMs from e-waste. Scaling cost-effective recycling technologies for recovering CM from e-waste is one immediate requirement identified through this research. There are two significant findings from the research in this report, namely a need for technological innovations and supply chain/recycling infrastructure.

Technology Innovations

- There is a dearth of technologies and investment for the recovery of PGMs from catalysts, but only 5 to 10% of the PGMs in electronics are recycled. Existing PGM recycling technologies need to be applied to a larger volume of e-waste to increase the percent recovery.
- Tin is currently recovered from e-waste at an industrial level, but recovery efforts need to be expanded to secure future tin supplies.
- Nickel has scaled recycling industries for sources other than e-waste, but the technology (traditional smelting) should be improved to lessen its environmental impact and increase its specific applicability to e-waste.
- Tungsten recovery from e-waste is currently prohibitively expensive. Cost-reduction techniques should be applied to existing laboratory-scale technologies to determine if tungsten recovery can be made economically viable.
- Recovering indium from EOL sources is generally more expensive than mining it from ore; work should be done to reduce costs and implement existing pilot technologies on a larger scale.
- There is a general need to fund more research in technologies to recover CMs from e-waste focused on specific components such as transparent screens (indium) and permanent magnets (REE) that contain high concentrations of high-value materials. There is a need for scaling up applicable technology for critical materials. Strategies to comprehensively recycle products containing multiple valuable materials are also required.
- Based on the patent search, there is a need for technologies that can recover the following CMs: REEs, titanium, tantalum, gallium, and arsenic.
    - Promising technologies – in particular, biometallurgical techniques – are available for REE recovery, but further research at higher TRLs is needed to validate them for industrial use.

        - Because REEs are essential for many defense technologies, such as guidance systems, establishing domestic REE recovery capabilities should be prioritized.
    - There is a lack of fundamental research on methods for titanium, gallium, and arsenic recovery.
        - Due to recent restrictions imposed by China on the export of gallium and germanium (Center for Strategic & International Studies 2023), developing technologies to enable the domestic recovery of gallium is of particular importance.
    - Several techniques are available to recover tantalum from e-waste, and more of these methods should be implemented on an industrial scale.
- Recycling rate of aluminum can be improved from 57%- specifically adapting technologies for recycling aluminum from e-waste can be a focus.

Table 6-1 highlights recommendations identified for the selected CMs based on the research in this report. Based on these needs, such as import reliance and market price (Table 1-1 in Chapter 1), along with information from the US Department of Energy's 2023 Critical Materials Assessment report (US Department of Energy), a tiered priority for technology investments for the selected CMs was established.

- Tier 1 included CMs that had an import reliance of >95% or a high (>$250 per kilogram) market price.
- Tier 2 included CMs that either 1) had an import reliance <95% or 2) had an import reliance >95% and a low (< $50 per kilogram) market price.

Supply Chain / Recycling Infrastructure

- Funding and investments required in cost-effective technologies to sort, classify and recover CM from multiple components within a given product are an immediate need to significantly improve the recycling process and integrate the R10 circular strategies.
- Policies and mandates for stricter recycling and waste management are required for increasing recycling around consumer and manufacture behavior.
- Investments are required in the infrastructure – specifically in connecting the manufacturers, distributors, consumers, and recyclers to be effective in all parts of the value chain.
- Programs such as EPR can be implemented to increase accountability and recycling efficiency.
- Manufacturers should be incentivized for better product designs and incorporation of the R10 circular strategies.

E-waste management is a complex and challenging problem. However, there is an opportunity to sustainably retrieve valuable CM from e-waste while reducing their environmental impact. Human health, social and environmental justice can be incorporated while developing CM recovery recycling technologies and recycling infrastructure. Our domestics supply chain can be secured through integration of a variety of efforts: technological innovations for recycling, better regulations, policy changes, connections between supply chain segments, EOL management, incentive structures around collection and recycling, incentives around better product design while incorporating R10 circular strategies and stakeholder behavior changes.

Table 6-1: CM investment priority.

Critical Material(s)	2022 Market Price (US Geological Survey 2023) ($/kg)	Import Reliance (US Geological Survey 2023)	Priority	Recommendations
Ga (Gallium)	420-640	100	Tier 1	There is a need for 1) identification of substitutes for GaAs integrated chips and 2) fundamental research on cost-effective methods for gallium recovery.
In (Indium)	250	100	Tier 1	Work should be performed to reduce indium recovery costs and encourage implementation of technologies beyond the pilot scale.
PGMs (Platinum group metals)	19,290 – 151,000	>66	Tier 1	Existing technologies for PGM recovery should be implemented for e-waste on a larger scale.
REEs (Rare Earth Elements)	1-2000	>95	Tier 1	Research on promising technologies, such as biometallurgical methods, should be performed at higher technology readiness levels to validate them for industrial use.
Ta (Tantalum)	150	100	Tier 1	Existing recovery options should be implemented on an industrial scale.
Al (Aluminum)	3	54	Tier 2	There is a need to 1) establish technologies that recover aluminum from e-waste specifically and 2) incorporate e-waste into existing recovery technologies/pathways.
As (Arsenic)	4	100	Tier 2	There is a need for 1) identification of substitutes for GaAs integrated chips and 2) fundamental research on cost-effective methods for arsenic recovery.
Ni (Nickel)	24	56	Tier 2	Existing nickel recovery technology should be improved to lessen its environmental impact and increase its specific applicability to e-waste.
Sn (Tin)	35	77	Tier 2	Existing tin recovery operations should be expanded to secure future tin supplies.
Ti (Titanium)	11	>95	Tier 2	Fundamental research on cost-effective methods for titanium extraction from e-waste should be performed.
W (Tungsten)	0.3	>50	Tier 2	Cost-reduction efforts should be made to determine if tungsten recovery can be made economically viable.

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Appendix A

A.1 Patent Search Criteria and Initial Results

The patent search was conducted using the database Patsnap. No application/publication date or language constraints were placed on the search – patents in any language from any time period were considered. The following key words were used to conduct the search:

TACD:("Rare earth" OR "Platinum group metals" OR Tantalum OR Aluminum OR Gallium OR Arsenic OR Indium OR Nickel OR Tin OR Titanium OR Tungsten OR platinum OR osmium OR iridium OR ruthenium OR rhodium OR palladium OR scandium OR yttrium OR Lanthanum OR cerium OR Praseodymium OR Neodymium OR promethium OR samarium OR Europium OR gadolinium OR Terbium OR Dysprosium OR holmium OR erbium OR Thulium OR Ytterbium OR Lutetium) AND TAC:(extract* OR recover* OR retriev* OR reclaim* OR salvag* OR recylc* OR leach*) AND TACD_ALL:("electronic waste" OR "ewaste" OR "e-waste" ((waste OR dispos* OR "end of life" OR component*) $W3 electr*))

The results of the search were exported as a table in Excel. A total of 738 patents were collected.

A.2 Methodology for Refined Patent Search

To refine the results of the initial search, a copy of the initial Excel sheet was made for each critical mineral discussed in this report. The abstracts of the patents were filtered, so only patents with abstracts containing the full name of a specified critical material were displayed in that critical material's sheet. For instance, dysprosium patents were investigated in the sheet named "Dy" and only patents whose abstracts contained the word "dysprosium" were displayed. The only exceptions to this search methodology were tin, terbium, and erbium. Because the letters "tin" frequently appear in other words, only patents whose abstracts contained "* tin *" (where * represents any series of characters) were displayed. Terbium and erbium are both components of the word "ytterbium," so their full names were used to filter patent abstracts, but patents that only referenced ytterbium were removed manually from the results. The results of this initial refining step were saved as a file in Excel. A manual review was performed on each critical material sheet to remove any irrelevant results. Patents were deemed irrelevant and removed if they met one or more of the following criteria:

1. The patent was about batteries and not intended for use with other categories of e-waste.
2. The patent was not about critical material recovery from e-waste and did not describe an idea that could feasibly be used for critical material recovery from e-waste. For example:
    a. A patent that disclosed a method for separating gallium and indium in a gallium-indium solution would be kept, even if its abstract did not specifically refer to e-waste, because it could feasibly be used for critical material recovery from e-waste.
3. The patent abstract was not in English.

The results were saved as a file in Excel (File name: Appendix A Attachment). Patents that did not meet the above criteria were counted and used to generate a plot of the number of patents returned for each critical material. This data, along with the data described in the following sections, was saved in a separate Excel file.

Critical materials that returned 3 or more patents were reviewed in greater detail to support the gap assessment. If a critical material returned 12 or fewer patents, it was reviewed manually, and each of its patents were categorized based on the main topic of the patent. For instance, if the patent was primarily about recovering REEs from waste permanent magnets, the patent was categorized under “Magnets.” If the patent was not clearly about one material or category of e-waste in particular, it was categorized under “General.”

If a critical material returned greater than 12 patents, keyword searches were used to gain insight into the gaps in the intellectual property space. Various keywords relevant to a specified critical material (ex. for indium, the keywords “tin oxide” or “solar” might be used) were used to filter abstracts. Keywords were selected based on findings from the earlier sections of the report. The number of patents with abstracts containing each key word/phrase were plotted. It is possible that some patents contained multiple keywords in their abstracts and were thus double counted (i.e., a patent may mention both “tin oxide” and “solar” and thus be counted in both of those categories), so the keyword search results do not necessarily sum to the total number of patents for a specified critical material.

Table A.1: Keyword search results for critical materials returning > 12 patents.

Critical Material	Keyword	Number of patents
Tin	Circuit board	75
	Solder	35
	Indium tin oxide / ITO	10
	PCB	4
	Phone	3
	Wiring board	2
	Computer	1
	PWB	0
	Monitor	0
	Solar	0
	Photovoltaic	0
	Fluorescent	0
Palladium	Circuit board	25
	Phone	9
	Catalyst	4
	Capacitor	3
	PCB	3
	Computer	2
	Automotive	1
	Wiring board	0
	Implant	0
	Hard drive	0
	PWB	0
	Monitor	0

Critical Material	Keyword	Number of patents
Aluminum	Circuit board	16
	Capacitor	7
	Frame	4
	Photovoltaic / PV	3
	Monitor	2
	LED	2
	Liquid crystal / LCD	2
	Phone	1
	Computer	1
	PCB	1
	Fluorescent	1
	Solar	0
	Wiring board	0
	PWB	0
Nickel	Circuit board	16
	Capacitor	6
	PCB	2
	Phone	2
	Steel	1
	Wiring board	0
	PWB	0
	Computer	0
	Monitor	0
Platinum	Circuit board	8
	Catalyst	3
	Computer	3
	PCB	2
	Automotive	2
	Phone	2
	PWB	0
	Wiring board	0
	Hard drive	0
	Implant	0
	Capacitor	0
	Monitor	0
Indium	Liquid crystal / LCD	15
	Panel	15
	Indium tin oxide / ITO	8
	Gallium	4
	Solar	1
	LED	1

Critical Material	Keyword	Number of patents
	CIG	1
	Phone	0
	Computer	0
	Photovoltaic / PV	0
	Fluorescent	0