A Fair Trade Circular Electronics Economy

Global Alliance for Repair and Refurbishment

Jaelyn Carr, Michael Kodysh, Sophie Lentz
Boston University 2025

Table of Contents

Abstract

The United States generates millions of tons of discarded electronics each year, yet recycling and recovery systems remain fragmented across states rather than coordinated through a single national framework.[1] While many devices collected at U.S. recycling sites are exported for processing abroad, others are mechanically shredded or landfilled at home, resulting in low material recovery and high environmental costs.[2] The problem lies both in the volume of waste the U.S. generates and in the design of its recycling systems; current state-level producer responsibility laws emphasize recycling quotas over reuse, and there is no federal mechanism to ensure that exported materials are handled safely or that domestic recycling is economically viable.[3] This paper argues that the term "e-waste" obscures the value embedded in discarded electronics and that U.S. policy must evolve from disposal to recovery. We propose an expanded framework, Electronic Product Recovery and Recycling (EPR2), that incentivizes repairable design, reuse, and fair-trade recovery partnerships to create a more circular and equitable global electronics economy.

Renaming "E-Waste"

A vital part in the success of promoting a circular expanded framework centers around rethinking the way we discuss "e-waste" as a concept. By labeling used electronic devices as "waste", we are promoting a disposable culture, pushing the linear economic expectation of discarding goods rather than reusing them. The term "e-waste" also lacks distinction between hazardous and non-hazardous materials, and ignores the larger complexity of categorizing used electronic materials. Instead, we propose shifting our relationship to electronic "waste" as something with value and the potential to be repaired and reused. With this new mindset, we instead will refer to "e-waste" materials interchangeably as used electronics and electronic materials throughout this paper, allowing us to move away from the former narrative labeling all

---

[1] Schumacher, Kelsea A., and Lawrence Agbemabiese. "E-waste Legislation in the US: An Analysis of the Disparate Design and Resulting Influence on Collection Rates Across States." Journal of Environmental Planning and Management 64, no. 6 (September 2, 2020): 1067–88. https://doi.org/10.1080/09640568.2020.1802237.

[2] Campbell, Katie, and Ken Christensen. "Where Does America's E-waste End up? GPS Tracker Tells All." PBS News, May 10, 2016. https://www.pbs.org/newshour/science/america-e-waste-gps-tracker-tells-all-earthfix#ref2

[3] Schumacher and Agbemabiese, "E-Waste Legislation in the US: An Analysis of the Disparate Design and Resulting Influence on Collection Rates Across States."

“e-waste” as hazardous[4]. There is a commonly perpetuated belief that all e-waste is hazardous and contains harmful substances, overshadowing all potential for refurbishment and repair.

With a circular model based on reuse, the life cycle of electronics becomes responsive to consumer needs rather than its former trajectory known as planned obsolescence[5]. Here, we are changing the way we relate to used electronics and their role in our lives. Once a temporary commodity, we now emphasize electronics’ potential to serve us longer than their planned life span. By prolonging the use of electronics, we encourage sustainable thinking, leading to increased innovation and reinvention in remanufacturing goods typically cast aside and disposed of.

Additionally, the re-framing of “e-waste” is necessary in part due to the lack of a cohesive definition for electronic waste. The typical definition describes “e-waste” as the electronic device and “its parts that have been discarded by its owner as waste without the intent of re-use.”[6] This refers to a variety of products in homes and businesses usually containing a circuit board with some sort of power supply[7]. However, categories of electronic waste are constantly expanding and adjusting to newly developed commodities, leaving it even more difficult to track, label, and properly manage. Moreover, definitions of “e-waste” focus on the aspect of disposal or use the term “end of life” to describe these used electronic products. In this paper, we argue that “end of life” is misleading, and instead encourage the idea of a continuous life cycle. While its original identity as a new product may be at an end, it still provides alternative use. Many valuable components within electronic devices can be recycled such as gold, copper, and aluminum, alongside other metals, plastics, and glass[8]. We focus mainly on gold and copper, as the extraction process for mining these metals is extremely dangerous to the

---

[4] Corwin, Julia. “The Hidden Environmental Labour of Electronics Repair.” The London School of Economics and Political Science, January 28, 2025. https://www.lse.ac.uk/research/research-for-the-world/sustainability/environment-electronics-repair.

[5] Planned obsolescence refers to a strategy where a product’s so-called “end of life” is built into the item itself by the manufacturer in order to get consumers to dispose of and purchase products at a faster rate.

[6] “What Is e-Waste,” n.d. https://globalewaste.org/what-is-e-waste/.

[7] A more extensive definition of “e-waste” includes items that fall under the categories of home appliances, home entertainment, communication and information technology devices, electronic utilities, office materials, and medical equipment. Items within these categories are known to contain PWBs (Printed Wiring Board), transistors, vacuum tubes, diodes, resistors, switches, motors, etc. Also included are products that use electricity to make heat or do work, manage information, and to send and store impulses.

[8] Fornalczyk, A., J. Willner, K. Francuz, and J. Cebulski. “E-waste as a Source of Valuable Metals.” *Archives of Materials Science and Engineering*. Vol. 63, October 2013. http://www.amse.acmsse.h2.pl/vol63_2/6325.pdf.

environment. We describe the process in detail further below which supports the argument to repair and reprocess used electronics as opposed to continuously mine for the necessary parts.

Environmental Harms of Traditional Mining Methods

Mining gold and copper inflicts severe environmental damages on surrounding ecosystems and communities causing land degradation, erosion, habitat loss and widespread water pollution. Open-pit mining is especially destructive because it requires removing massive volumes of rock that have remained undisturbed for thousands or millions of years, destabilizing landscapes and accelerating erosion. Gold and copper deposits form through slow (millions of years) geological processes involving heat, pressure and circulating fluids: copper through the rise of hot, metal-rich hydrothermal fluids rising from magma bodies that deposit copper minerals in fractures of rock, and gold through similar hydrothermal systems or through long-term concentration in ancient volcanic/sedimentary environments.[9] [10] Many of the world's largest gold and copper deposits occur in arid and semi-arid regions where soils develop extremely slowly because the low rainfall suppresses chemical weathering, the key process that breaks down rock into fertile soil.[11] Once mining disrupts these fragile systems, degradation and human-caused erosion is long-lasting and often irreversible.[12]

Gold mining is particularly harmful due to cyanidation, a method that has dominated the industry for nearly 140 years and accounts for roughly 80% of global gold extraction.[13] In this process, low-grade gold ore is crushed, dispersed across large fields, and then sprayed with a

---

[9] Heinrich, Christoph A. "The Chain of Processes Forming Porphyry Copper Deposits—An Invited Paper." *Economic Geology* 119, no. 4 (June 1, 2024): 741–69. https://doi.org/10.5382/econgeo.5069.
[10] Russell, Brad. "Porphyry and Epithermal Deposits: Formation, Exploration, and Economic Impact." Discovery Alert, April 4, 2025. https://discoveryalert.com.au/porphyry-and-epithermal-deposits-formation-exploration-and-economic-impact/.
[11] Yryszhan Zhakypbek et al., "Effects of Gold Mining on the Physicochemical Properties of Soils at the Akbakai Gold Deposit," Engineered Science 36 (2025): 1670, https://dx.doi.org/10.30919/es1670
[12] Xu, Hailiang, Qiao Xu, Guankui Gao, Haitao Dou, Abdul Waheed, and Aishajiang Aili. "Advances in Ecological Restoration of Mining-Impacted Landscapes: Techniques, Case Studies, and Key Challenges." Environmental Research 290 (December 5, 2025): 123485. https://doi.org/10.1016/j.envres.2025.123485.
[13] Du Plessis, C.A., H. Lambert, R.S. Gärtner, K. Ingram, W. Slabbert, and J.J. Eksteen. "Lime Use in Gold Processing – a Review." Minerals Engineering 174 (October 27, 2021): 107231. https://doi.org/10.1016/j.mineng.2021.107231.

cyanide solution that dissolves the gold.[14] [15] The liquid then seeps down until it hits a rubber lining layer and then collects into pools containing the gold-cyanide solution.[16] The resulting liquid waste, known as leachate, is a toxic substance that contaminates groundwater, surface water, and soil.[17] The most often failing points of the tailing ponds lie in the dams that keep them secured.[18] The tailing dams are prone to failure because they are typically contained by earthen dams which are embankments made from soil, mine waste, and rock rather than reinforced concrete.[19] Unlike water-retention dams, which are engineered to strict stability standards and built from dense, compacted materials, earthen dams rely on the strength of loose, unconsolidated sediments that are far more vulnerable to internal seepage and erosion.[20] According to the International Commission on Large Dams (ICOLD), tailings dams fail at rates 10–100 times higher than conventional water dams causing catastrophic release of cyanide-contaminated slurry.[21] Even though many modern dams include a liner designed to separate soil from leachate, these liners are vulnerable to erosion and tearing, rendering them ineffective over time.[22] Once a dam is compromised, contamination poses serious risks to wildlife, vegetation, and human health.[23]

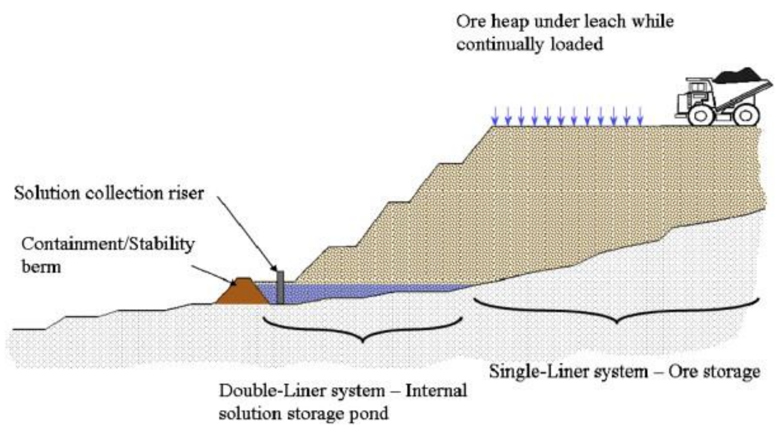
In November 2023, a tailing dam at the El Corazón gold mine in Imbabura, Ecuador suffered a structural failure that released cyanide-bearing process water and fine tailings into surrounding water and soil.[24] Post-spill testing documented 60.8 mg/L of total cyanide at the

---

[14] Hoffmann, and James Edward. "Gold Processing | Refining, Smelting & Purifying." Encyclopedia Britannica, July 26, 1999. https://www.britannica.com/technology/gold-processing/Mining-and-concentrating.
[15] Earthworks. "Cyanide Use in Gold Mining - Earthworks." Earthworks, June 11, 2022. https://earthworks.org/issues/cyanide/.
[16] Earthworks, "Cyanide Use in Gold Mining"
[17] Johnson, Craig A. "The Fate of Cyanide in Leach Wastes at Gold Mines: An Environmental Perspective." Applied Geochemistry 57 (June 11, 2014): 194–205. https://doi.org/10.1016/j.apgeochem.2014.05.023.
[18] Earthworks, "Cyanide Use in Gold Mining"
[19] IndustriALL. "What Are Tailings Dams?," March 1, 2019. https://www.industriall-union.org/why-you-need-to-know-about-tailings-dams.
[20] IndustriALL. "What Are Tailings Dams?"
[21] Azam, Shahid, and Qiren Li. "Tailings Dam Failures: A Review of the Last One Hundred Years." Geotechnical News, December 2010. https://ksmproject.com/wp-content/uploads/2017/08/Tailings-Dam-Failures-Last-100-years-Azam2010.pdf.
[22] "Risks of Leaks and Seepage From Improper Heap Leach Pad Design," n.d. https://www.btlliners.com/risks-of-leaks-and-seepage-from-improper-heap-leach-pad-design.
[23] Earthworks, "Cyanide Use in Gold Mining"
[24] Emerman, Steven H. and Malach Consulting. "Causes and Consequences of the Failure of the Tailings Dam at the Agroindustrial El Corazón Gold Mine on November 4, 2023, Imbabura Province, Northern Ecuador," 2024. https://earthworks.org/wp-content/uploads/2025/03/El_Corazon_Report_Emerman.pdf.

discharge point, over 600 times Ecuador's legal limit of 0.1 mg/L, along with elevated concentrations of arsenic, iron, manganese, and mercury.[25] According to the technical assessment commissioned by Earthworks, the spill contaminated agricultural land, impacted water users, and posed acute toxicity risks to aquatic ecosystems.[26] The failure was traced to a tear in the geomembrane liner, inadequate drainage, and structural weaknesses in the outer embankment, allowing cyanide-rich tailings to escape directly into the environment.[27]

Another example of tailing ponds causing harm to wildlife comes from Nevada's gold mine leachate storing ponds, (also known as mill-tailing ponds) which store leachate in open air-basins. Since they resemble natural bodies of water, migrating birds attempt to land on or drink from them, leading to widespread poisoning. Between the mid-1980s and mid-1990s these ponds have killed more than 9,500 birds.[28]



[25] Emerman, Steven H. and Malach Consulting. "Causes and Consequences of the Failure of the Tailings Dam at the Agroindustrial El Corazón Gold Mine on November 4, 2023, Imbabura Province, Northern Ecuador"
[26] Emerman, Steven H. and Malach Consulting. "Causes and Consequences of the Failure of the Tailings Dam at the Agroindustrial El Corazón Gold Mine on November 4, 2023, Imbabura Province, Northern Ecuador"
[27] Emerman, Steven H. and Malach Consulting. "Causes and Consequences of the Failure of the Tailings Dam at the Agroindustrial El Corazón Gold Mine on November 4, 2023, Imbabura Province, Northern Ecuador"
[28] Henny, Charles J., Robert J. Hallock, and Elwood F. Hill. "Cyanide and Migratory Birds at Gold Mines in Nevada, USA." Ecotoxicology 3, no. 1 (March 1, 1994): 45–58. https://doi.org/10.1007/bf00121387.

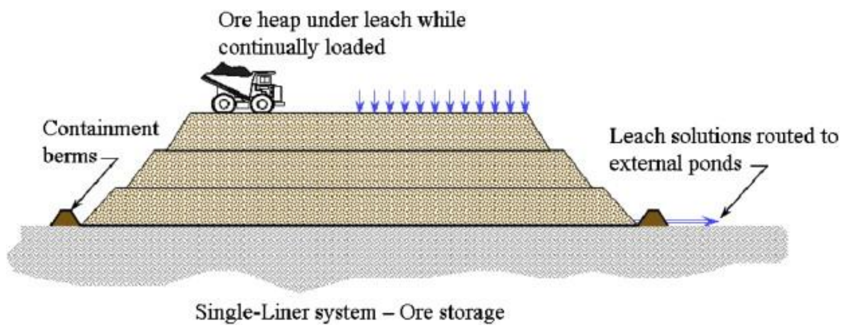


Figure 1: Diagram showing the cyanidation process[29]

Traditional copper mining, especially open-pit mining which accounts for 80% of global copper production, causes substantial environmental damage through the extensive soil and rock displacement (explained earlier) and acid mine drainage (AMD).[30] Acid mine drainage is the outflow of highly acidic water containing dissolved heavy metals and metalloids like arsenic, lead, iron, cadmium, and manganese. AMD forms when sulfide minerals and heavy metals, previously isolated from air and water for millions of years, are exposed during mining and react with the elements, producing sulfuric acid laden with dissolved metals. 80% of global copper production is extracted from sulfide minerals, since pure copper ore is extremely rare, proving that AMD is a widespread consequence of copper mining.[31] This solution seeps into the surrounding soil and water, contaminating them, devastating wildlife depending on the habitats for survival and rendering it unsafe for human consumption. AMD lowers water pH to levels that are lethal to aquatic organisms, degrades soil health, and enables toxins to travel long distances through watersheds, causing persistent environmental damage long after mining ends.

The Bingham Canyon Mine in Utah, one of the largest open pit copper mines, has caused significant environmental damage in the region surrounding Salt Lake City. The mine has been identified as a major source of environmental contamination, ranking as the second most polluting mine in the U.S. by toxic releases, prompting legal responses from federal and state agencies. Mining operations there released hazardous substances including selenium, copper,

[29] Lupo, John F. "Liner System Design for Heap Leach Pads." Geotextiles and Geomembranes 28, no. 2 (December 10, 2009): 163–73. https://doi.org/10.1016/j.geotexmem.2009.10.006
[30] "Ministry of Mines, Government of India, Home," n.d. https://mines.gov.in/webportal/copper.
[31] Izydorczyk, Grzegorz, Katarzyna Mikula, Dawid Skrzypczak, Konstantinos Moustakas, Anna Witek-Krowiak, and Katarzyna Chojnacka. "Potential Environmental Pollution From Copper Metallurgy and Methods of Management." Environmental Research 197 (March 20, 2021): 111050. https://doi.org/10.1016/j.envres.2021.111050.

arsenic, lead, zinc, and cadmium near the Great Salt Lake, a critical biological resource for migratory birds, regional wildlife and their supporting ecosystems.[32] According to federal biologists, the release of these hazardous pollutants has harmed natural resources including wetlands, marshes, freshwater habitats, playas and riparian areas.[33] Over decades, waste rock piles and improperly contained wastewater have leached AMD into the groundwater, creating a contamination plume. The EPA estimates it covers more than 72 square miles toward the Jordan River, making groundwater undrinkable for thousands of Salt Lake City residents.[34] A settlement was reached, requiring the mine company to pay $37 million into a trust fund to complete significant remediation efforts including interception wells and water treatment systems for the surrounding area to prevent further spread.[35][36] Due to the severity and long term consequences, the north part zone of the mining site is still on the EPA's list of proposed Superfund sites.

Another example of acid mine drainage damaging the environment is the Berkeley Pit in Butte, Montana, a large open-pit copper mine that operated from 1955 until 1982.[37] During active operation, vast amounts of rock were excavated and stockpiled nearby, while continuous water pumping was required to prevent groundwater from flooding the pit. After mining ceased in 1982, the de-watering pumps were shut off and pipes not maintained. Groundwater refilled the pit, interacting with exposed sulfide minerals, producing AMD with pH values at 2.5, far below safe levels for any ecosystem.[38] [39] This water now fills the pit to about 900 feet deep of acidic, metal-contaminated water making it inhospitable to most life.[40] The Berkeley Pit became part of the Silver Bow Creek/Butte Area Superfund showing that this is a consistent, serious problem. AMD has caused documented wildlife deaths, including 342 snow geese in 1996 and 3,000 more

---

[32] Earthworks. "Earthworks Factsheet Problems with Bingham Canyon Mine." Earthworks Factsheet. Earthworks, 2006. https://earthworks.org/wp-content/uploads/2021/09/FS_Problems_BinghamCanyon_2011_low.pdf.
[33] Earthworks. "Earthworks Factsheet Problems with Bingham Canyon Mine."
[34] Earthworks. "Earthworks Factsheet Problems with Bingham Canyon Mine."
[35] Earthworks. "Earthworks Factsheet Problems with Bingham Canyon Mine."
[36] Department of Justice. "Second Largest U.S. Copper Producer Implements Comprehensive Cleanup at Bingham Canyon Mine in Utah," July 9, 2007. https://www.justice.gov/archive/opa/pr/2007/July/07_enrd_488.html.
[37] Desonie, Dana, PhD. "Environmental Impacts of Mining." CK-12 Foundation, December 2, 2025. https://flexbooks.ck12.org/cbook/ck-12-middle-school-earth-science-flexbook-2.0/section/21.6/related/rwa/the-berkeley-pit/.
[38] Theme, Education Zone Pro by Rara. "Berkeley Pit." Butte-Silver Bow Public Archives, December 16, 2020. https://buttearchives.org/berkeley-pit/.
[39] Desonie, Dana, PhD. "Environmental Impacts of Mining."
[40] Theme, Education Zone Pro by Rara. "Berkeley Pit."

in 2016 after landing on the acidic lake.[41] [42] Ongoing remediation efforts such as the Horseshoe Bend water treatment plant cleanses millions of gallons per day to prevent the drainage from spreading to Silver Bow Creek and downstream ecosystems.[43] Active monitoring is necessary to protect both the environment and human health.

A recent toxicological study examined runoff from the Sulitjelma copper mine in Norway, finding elevated concentrations of dissolved metals including copper (~18.3 mg/L), magnesium (~46.7 mg/L), aluminum (~20.2 mg/L), iron (~19.8 mg/L), and zinc (~10.6 mg/L).[44] For comparison, the EPA's mandated standards for water considered safe are as follows: ≤1.3 mg/L for copper, <10–40 mg/L for magnesium, ≤0.2 mg/L for aluminum, ≤0.3 mg/L for iron, and ≤5 mg/L for zinc.[45] Laboratory experiments showed that zebrafish larvae exposed to highly diluted AMD (as low as 0.1% and 0.45% of the raw AMD), experienced reduced body size and eye size, abnormal development, decreased locomotion, and increased oxygen consumption, indicating lethal impacts on aquatic organisms.[46]

Human health impacts are also often documented in communities near contaminated mining sites. A study comparing 116 residents of Butte and 86 residents of Bozeman, a town approximately 90 miles from Butte, found that hair and blood samples from Butte residents had statistically significantly higher concentrations of arsenic (As), aluminum (Al), cadmium (Cd), copper (Cu), manganese (Mn), and molybdenum (Mo) than those from the control.[47] Elevated

[41]LeCain, Timothy. "Death in Butte's Berkeley Pit: What 342 Dead Snow Geese Tell Us About the Nature of Humans." Digital Commons @ Montana Tech, n.d. https://digitalcommons.mtech.edu/public_lectures_mtech/60/.
[42]LeCain, Timothy. "Death in Butte's Berkeley Pit: What 342 Dead Snow Geese Tell Us About the Nature of Humans."
[43]Earthworks. "Earthworks Factsheet Problems with Bingham Canyon Mine."
[44]Varshney, Shubham, Mikkel Lundås, Prabhugouda Siriyappagouder, Torstein Kristensen, and Pål A. Olsvik. "Ecotoxicological Assessment of Cu-rich Acid Mine Drainage of Sulitjelma Mine Using Zebrafish Larvae as an Animal Model." Ecotoxicology and Environmental Safety 269 (December 7, 2023): 115796. https://doi.org/10.1016/j.ecoenv.2023.115796.
[45]US EPA. "National Primary Drinking Water Regulations | US EPA," December 1, 2025. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations.
[46] Varshney, Shubham, Mikkel Lundås, Prabhugouda Siriyappagouder, Torstein Kristensen, and Pål A. Olsvik. "Ecotoxicological Assessment of Cu-rich Acid Mine Drainage of Sulitjelma Mine Using Zebrafish Larvae as an Animal Model."
[47]Hailer, M. Katie, Christopher P. Peck, Michael W. Calhoun, Robert F. West, Kyle J. James, and Steven D. Siciliano. "Assessing Human Metal Accumulations in an Urban Superfund Site." Environmental Toxicology and Pharmacology 54 (June 27, 2017): 112–19. https://doi.org/10.1016/j.etap.2017.06.001.

levels of these minerals in the body are associated with increased cancer risk, cardiovascular disease, damages to kidneys and bones, and impairment of organ and nervous system function.[48]

Used Electronics Reprocessing (UER)

As worldwide electrification accelerates through artificial intelligence advancements, electric vehicles, battery-dependent technology in daily-use objects, demand for copper is expected to increase 70% by 2050.[49] Given the severe environmental costs of primary mining practices, including habitat destruction and documented mortality of migratory birds and aquatic species, it is crucial to reduce reliance on traditional mining and expand large-scale recycling of available resources.

We introduce the term Used Electronics Reprocessing (UER) as a replacement for the traditional mining framework, which continues to degrade ecosystems and threaten human health. UER refers to the processing of used electronics such as smartphones, computers, batteries, and wiring systems to recover valuable metals including copper, gold, etc. to be used in the manufacturing of new electronics. Since traditional mining is inherently destructive, the commonly used term 'urban mining' fails to distinguish sustainable electronic reprocessing from environmentally damaging extraction practices. The word 'mining' itself carries a strong stigma, encompassing not only environmental harm but also community disruption, the framing of miners as victims, and gender bias within the industry, making it an inaccurate representation of UER. As millions of tons of electronic devices are discarded each year, continuing to use terminology rooted in extractive practices undermines the sustainability goals of electronic reprocessing and should not remain part of our vocabulary.

Recycling copper requires up to 85% less energy than mining copper containing ore, substantially reducing greenhouse gas emissions while avoiding costs associated with mining, processing, and transporting.[50] Moreover, metals embedded in electronics are already refined to

---

[48] Hailer, M. Katie, Christopher P. Peck, Michael W. Calhoun, Robert F. West, Kyle J. James, and Steven D. Siciliano. "Assessing Human Metal Accumulations in an Urban Superfund Site."
[49]The Oregon Group. "Global Copper Demand to Increase 70% by 2050, to More Than 50 Mt - the Oregon Group - Critical Minerals And." The Oregon Group - Investment Insights, November 5, 2024. https://theoregongroup.com/commodities/global-copper-demand-to-increase-70-by-2050-to-more-than-50-mt/.
[50]Directory, Sustainability. "Urban Mining Practices → Term." Energy → Sustainability Directory, December 2, 2025. https://energy.sustainability-directory.com/term/urban-mining-practices/.

purities 10 times higher than rich ore content, making recovery less resource intensive than processing low-grade ore.[51] Recovering metals from used electronics therefore represents both an environmental and economic advantage. The concept of extracting gold from technology is already being implemented and explored by scientists, companies, and countries. For example, the Royal Mint in the United Kingdom operates a Precious Metals Recovery facility that processes used electronics to extract high-purity gold, reducing reliance on traditional mining and converting it into products like jewelry and investment-grade bars.[52]

Used Electronic Reprocessing offers a scalable, cleaner, and economically efficient alternative for sourcing critical metals without further degrading ecosystems or exposing communities to toxic contamination. By transforming discarded electronics into a reliable source of high-purity materials, UER closes the resource loop, reduces dependence on destructive mining practices, gives used electronics a new life and redefines how society sources the metals essential to modern technological systems.

Structural and Economic Barriers to Efficient Domestic Recycling

UER would provide an environmentally safe method for sourcing the high amount of valuable metals that are normally discarded. The United States generates between 2.9 million to 6 million tons of used, out-of-service, or surplus electronic equipment annually.[53] A large share of this material is reported in U.S. and international datasets as "e-waste," even though a portion of it is still repairable, reusable, or valuable for parts recovery. Globally, an estimated 62 billion kilograms of material was classified under the e-waste category in 2022, but only 22.3 percent (13.8 billion kg) was documented as properly collected and recycled, revealing how much of

---

[51] Vuppaladadiyam, Sai Sree Varsha, Bennet Sam Thomas, Chandan Kundu, Arun K. Vuppaladadiyam, Huabo Duan, and Sankar Bhattacharya. "Can E-waste Recycling Provide a Solution to the Scarcity of Rare Earth Metals? An Overview of E-waste Recycling Methods." The Science of the Total Environment 924 (March 5, 2024): 171453. https://doi.org/10.1016/j.scitotenv.2024.171453.

[52] "New Factory Extracting Gold From E-Waste Unveiled by the Royal Mint," n.d. https://www.royalmint.com/aboutus/press-centre/new-factory-extracting-gold-from-e-waste-unveiled-by-the-royal-mint/.

[53] Alma Kelly, "Electronics Recycling and Disposal in Boston, MA," eWaste Solutions, July 16, 2025, https://ewastesolutionsusa.com/electronics-recycling-boston/; Ravi Soopramanien and Pamela Usta, "E-Waste: A Bigger Problem Than You Think | Stanford Law School," Stanford Law School, October 21, 2015, https://law.stanford.edu/2015/10/21/e-waste-bigger-problem-think/.

“e-waste” is actually a mixed stream of reusable devices, parts, and true discards.[54] This matters because once a material is named “waste” it is governed as waste and is more easily steered toward shredding or unregulated export, even when reuse would generate more value.

Global flows of discarded and surplus electronics contain an estimated 57 billion USD in recoverable metals and plastics.[55] This includes roughly 1,900 kilotonnes of copper (≈ 11.4 billion USD), 0.3 kilotonnes of gold (≈ 11.2 billion USD), and 8,600 kilotonnes of plastics (≈ 13.3 billion USD).[56] If a greater share of the U.S. flow were recovered, recycled materials could partially displace the need for primary mining and cut greenhouse gas emissions by up to 80 percent compared with virgin extraction of equivalent materials.[57] Yet, only approximately 25 percent of U.S. electronic materials are actually recycled, which means that most of the embedded value remains unrealized.[58] Domestic recycling faces several interrelated economic and structural barriers that make large-scale, efficient recovery of electronic materials in the United States difficult to achieve. As illustrated in *Figure 2*, the current U.S. electronics lifecycle is primarily linear, with most end-of-life products moving toward disposal rather than reuse or material recovery. Given these reasons, we advocate for a unified, circular export and recovery framework.

---

[54] Vanessa Forti et al., “The Global E-waste Monitor: Quantities, Flows, and the Circular Economy Potential,” Report (Bonn, Germany: United Nations University/UNITAR SCYCLE Programme, 2020), https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

[55] Kang Liu et al., “A Global Perspective on E-waste Recycling,” *Circular Economy* 2, no. 1 (February 24, 2023): 100028, https://doi.org/10.1016/j.cec.2023.100028.

[56] ibid.

[57] International Energy Agency, “Recycling of Critical Minerals” (International Energy Agency, 2024), https://www.iea.org/reports/recycling-of-critical-minerals/executive-summary.

[58] Abu Bakri Ibrahim, “How Much E-waste Is Recycled in the US?,” E-Waste Collection & Recycling Association, June 21, 2024, https://ewcra.org/2024/06/21/e-waste-recycled-in-us/.

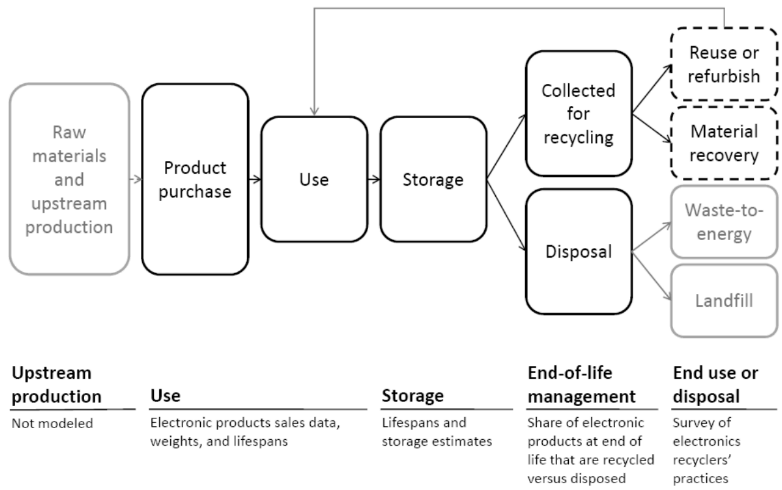


Figure 2: Lifecycle flow of electronic products in the United States. Solid bordered boxes represent lifecycle stages modeled in the EPA study; dashed boxes represent stages based on recycler survey data; gray boxes represent unmodeled stages. Adapted from U.S. Environmental Protection Agency.[59]

I. Economic Barriers

Domestic recycling in the United States faces a series of interconnected economic challenges that constrain the recovery of electronic materials, limiting both environmental and financial returns. As of August 2025, the formal electronic goods recycling sector in the United States includes roughly 860 businesses employing about 58,000 people and generating roughly 27.7 billion USD in annual revenue.[60] Despite this formal infrastructure, many U.S. recyclers operate with narrow profit margins and little incentive for new entrants to fill the capacity needed to process the nation's own electronic products.[61]

The operation is labor intensive and costly, as dismantling, sorting, and safely processing complex devices designed for rapid obsolescence often requires manual work that cannot easily be automated.[62] Labor costs in the U.S. are substantially higher than in countries that import used

[59] U.S. Environmental Protection Agency, "Electronics Waste Management in the United States Through 2009" (U.S. Environmental Protection Agency, 2011), https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100BKKL.PDF.
[60] Dmitry Diment, "Electronic Goods Recycling in the US - Market Research Report (2015-2030)" (IBISWorld, August 2025), https://www.ibisworld.com/united-states/industry/electronic-goods-recycling/4510/.
[61] U.S. Government Accountability Office, "Science & Tech Spotlight: Consumer Electronics Recycling" (U.S. Government Accountability Office, August 31, 2020), https://www.gao.gov/assets/gao-20-712sp.pdf.
[62] Aggregates Equipment, Inc, "The Challenges of E-Waste Recycling," AEI Screens, June 3, 2025, https://aeiscreens.com/news/the-challenges-of-e-waste-recycling/.

electronics.[63] As a result, recyclers often export unsorted shipments that combine recoverable materials with scrap to regions where labor and processing costs are lower, effectively externalizing the environmental risks and the remaining material value.[64] Profitability is further undermined by commodity price volatility, particularly in metals such as copper, aluminum, and gold. When global prices fall for these materials, recyclers' margins shrink, and some firms respond by reducing operations or relying more heavily on lower-cost disposal methods, including shredding or export in certain cases.[65]

Establishing and maintaining advanced recovery facilities also demands significant fixed capital investment and infrastructure costs, which must be paid regardless of throughput, leaving operators financially exposed when commodity prices decline. Recycling electronics requires specialized machinery, ranging from shredders and automated separation systems to hydrometallurgical recovery units and smelting furnaces; pollution controls such as air filtration, acid scrubbers, and wastewater treatment systems; and compliance with safety regulations established by the EPA and OSHA.[66]

Moreover, the design of electronic products themselves compounds the problem. Most devices are constructed with multiple materials fused together, such as plastics, glass, rare metals, and toxic substances.[67] These combinations produce heterogenous assemblies that complicate disassembly, reduce recovery yields, and increase contamination risks.[68] These design choices are reinforced by planned obsolescence, a profit driven strategy in which manufacturers intentionally limit product lifespan to stimulate new purchases.[69] Many manufacturers design products with components that inhibit repair or refurbishment, such as difficult-to-replace batteries, sealed or adhesive-mounted displays, cases, and battery assemblies, or non-standard

---

63 Soopramanien and Usta, "E-Waste: A Bigger Problem Than You Think | Stanford Law School."
64 Liu et al., "A Global Perspective on E-Waste Recycling."
65 Janice Lee et al., "Don't Throw Away The Opportunity in E-Waste," Boston Consulting Group, June 26, 2023, https://www.bcg.com/publications/2023/seizing-opportunity-ewaste-recycling.
66 Liu et al., "A Global Perspective on E-Waste Recycling" ; United Nations Environment Programme and International Solid Waste Association, "Global Waste Management Outlook" (United Nations Environment Programme, 2015), https://www.unep.org/resources/report/global-waste-management-outlook.
67 Aggregates Equipment, Inc, "The Challenges of E-Waste Recycling."
68 Liu et al., "A Global Perspective on E-Waste Recycling"
69 Jenni Ylä-Mella, Riitta L. Keiski, and Eva Pongrácz, "End-of-Use Vs. End-of-Life: When Do Consumer Electronics Become Waste?," *Resources* 11, no. 2 (February 7, 2022), https://doi.org/10.3390/resources11020018.

fasteners that restrict access to internal components.[70] These design barriers limit disassembly and repair, effectively hampering the recovery of otherwise valuable materials.

Finally, there are logistical challenges that add further pressure to recyclers' already narrow profit margins. Transporting bulky or unsorted loads to processing facilities is expensive and energy intensive, especially when recyclers must comply with hazardous material regulations during transit.[71] Once received, recyclers manage a diverse mix of electronic equipment that require manual disassembly and separation into recyclable, reusable, and hazardous components.[72] Maintaining the purity of recovered materials requires warehouse space, meticulous inventory management to prevent cross-contamination between material streams, and quality-control systems such as optical sorting and near-infrared (NIR) spectroscopy, which are used to separate metals, plastics, and other materials within mixed electronic loads—all of which impose additional costs.[73] These logistical costs make domestic recovery less competitive than sending materials to regions with established reuse and refurbishment markets, where labor is cheaper and secondary markets for used electronic equipment are already established.[74]

II. Structural Barriers

1. U.S. State Legislation

Within the United States, regulatory fragmentation highly compounds the economic barriers described above. Although 25 states have enacted legislation addressing used electronics, these laws differ substantially in both intent and coverage. Minnesota, Indiana, and Pennsylvania each implement versions of disposal bans that restrict electronics from entering municipal waste streams; yet the specific products covered range from narrow categories such as

---

[70] Dylan A. Hazelwood and Michael G. Pecht, "Life Extension of Electronic Products: A Case Study of Smartphones," *IEEE Access* 9 (January 2021): 144726–39, https://doi.org/10.1109/access.2021.3121733.
[71] U.S. Environmental Protection Agency, "Electronics Waste Management in the United States Through 2009."
[72] ibid.
[73] "Precise E-Waste Sorting With Sesotec Systems - Sesotec GmbH," n.d., https://www.sesotec.com/en/applications/recycling/electronic-waste.
[74] Frank Adu and George Baffour Awuah, "Towards a Circular Economy: E-waste Management in Africa" (African Center for Economic Transformation, May 12, 2025), https://acetforafrica.org/research-and-analysis/reports-studies/reports/towards-a-circular-economy-e-waste-management-in-africa/.

cathode ray tube (CRT) monitors and televisions to more expansive definitions that include all computer monitors and laptops.[75] These three states also provide examples of manufacturer operated programs, where manufacturers are required to collect and recycle, either themselves or through the proper arrangements, a certain percentage of the devices they sell. These programs supply further disconnect in legislation, as different programs vary in the percentage of materials manufacturers are responsible for (i.e. between 60-80%), as well as the range of device types that manufacturers are required to recycle.[76]

Other states, such as Washington, have no disposal ban on electronic materials, but instead enforce a state operated recycling program, differing from the previous states by requiring manufacturers to be registered with the Washington Department of Ecology in order to remain a vendor in the state of Washington. Additionally, manufacturers must annually finance the recycling of a weight of products equivalent to their proportional market share and the total volume of electronics collected in the state.[77]

Additionally, California and Utah are two states that provide a unique framework for managing used electronics. California's Covered Electronic Waste Recycling Program (CEW) targets consumers by requiring a fee between $4 to $6 USD, depending on the size of the screen on the electronic device. This fee is put towards statewide collection and recycling programs.[78] It's important to note that this regulation only applies to "covered electronic devices" which are defined as a video display device with a screen measuring more than 4 inches diagonally. While this is an beneficial regulation, it is not applied consistently throughout the U.S., and fails to account for other electronics with valuable recovery potential. Utah, on the other hand, employs an electronic recycling education program where manufacturers instruct consumers on how to

[75] ERI. "Minnesota State E-Waste Legislation - ERI," June 30, 2025. https://eridirect.com/sustainability/us-legislation/minnesota/.
[76] ERI. "Indiana State E-Waste Legislation - ERI," June 30, 2025. https://eridirect.com/sustainability/us-legislation/indiana/.
[77] "Manufacturers - Washington State Department of Ecology," n.d. https://ecology.wa.gov/regulations-permits/guidance-technical-assistance/electronics-ecycle-guidance-and-reports/manufacturers.
[78] California, State Of. "Electronic Waste Recycling Fee - CalRecycle Home Page." CalRecycle Home Page, n.d. https://calrecycle.ca.gov/electronics/recyclingfee/.

properly recycle electronic materials.[79] Other states have a combination of the aforementioned legislation types, or none at all.

These legislative examples exhibit the broader lack of cohesion in electronics management across the United States. This "patchwork" framework of state-specific regulations poses problems for properly tracking, labeling, and coordinating the flow of used electronic materials. Under each state's regulations or lack thereof, components of an electronic recycling infrastructure such as "product scope, covered entities, financing mechanism, convenience standards, governing structure, education/outreach requirements, third party qualifications, and performance goals" all target different objectives in each state, making it extremely difficult to not only develop a cohesive system for processing used electronic materials, but to even generate a common definition for "e-waste," complicating efforts to determine what should be collected, how it should be processed, and whether and under what conditions it may be exported. This regulatory variability ultimately undermines efficiency, increases compliance costs for manufacturers and recyclers operating across state lines, and limits the overall productivity of U.S. e-waste management.[80]

2. Federal Regulations

This ambiguous assortment of state legislation stems from the absence of reasonable federal standards for used electronics. U.S. involvement in regulating hazardous waste began in 1976 with the enactment of the Resource Conservation and Recovery Act (RCRA), providing legal objectives for "waste" materials. A later amendment in 1984 known as the Hazardous and Solid Waste Amendment (HWSA), governed the act of managing hazardous waste from "cradle to grave."[81] These statutes have jurisdiction over materials that comply with the EPA's definition of solid waste, which then allows them to be classified as hazardous waste under RCRA, and requires a permit from the EPA for all storage, treatment, or disposal of hazardous waste (characteristics including reactivity, corrosivity, ignitability, or toxicity). There are severe limitations to these parameters, as the only "e-waste" considered hazardous by the EPA is items

[79] Schumacher, "E-waste legislation in the US: An analysis of the disparate design and resulting influence on collection rates across States."
[80] ibid.
[81] US EPA. "Resource Conservation and Recovery Act (RCRA) Overview | US EPA," September 5, 2025. https://www.epa.gov/rcra/resource-conservation-and-recovery-act-rcra-overview.

containing cathode ray tubes with lead, meaning that only CRT TVs and monitors are restricted from disposal and are traced under RCRA regulations.

Additionally, this existing federal legislation contains numerous exemptions that significantly weaken its effectiveness. For example, households and small businesses, classified as "small quantity generators," are exempt from most RCRA regulations and therefore able to dispose of electronic materials into landfills without legal repercussions. A further challenge arises from the inconsistent classification of used electronics, which can be labeled either as solid waste or as "valuable commodities with significant economic value."[82] This ambiguity creates regulatory loopholes: devices that would normally be considered hazardous waste can be reclassified and thereby exempted from RCRA oversight, including notification requirements for export. Because RCRA only regulates exports explicitly identified as hazardous waste, a substantial volume of used electronics falls outside federal jurisdiction and cannot be reliably tracked through its downstream life cycle. This lack of communication also leaves processing facilities abroad unprepared for the materials it is receiving. While the U.S. still requires exporters to notify the receiving country, there is no system in place to properly ensure these countries have the capacity to safely manage the materials.[83]

The gaps within RCRA not only complicate domestic oversight but also position the United States out of harmony with the international framework governing hazardous waste, known as the Basel Convention. This multilateral agreement controls the flow of hazardous waste across borders in attempts to protect human and environmental health, especially in countries that lack adequate processing facilities for hazardous waste.[84] A key component of the Basel Convention is the concept of "prior informed consent" (PIC), requiring exporters to obtain

[82] US EPA. "Regulatory Exclusions and Alternative Standards for the Recycling of Materials, Solid Wastes and Hazardous Wastes | US EPA," September 25, 2025. https://www.epa.gov/hw/regulatory-exclusions-and-alternative-standards-recycling-materials-solid-wastes-and-hazardous.

[83] Meidl, Rachel. "Closing the Loop on the World's Fastest-growing Waste Stream: Electronics." *Baker Institute for Public Policy*, June 14, 2023. https://www.bakerinstitute.org/research/closing-loop-worlds-fastest-growing-waste-stream-electronics#_edn130.

[84] Basel Convention. "Basel Convention > the Convention > Overview." Copyright 2011 by Basel Convention, n.d. https://www.basel.int/theconvention/overview/tabid/1271/default.aspx.

permission from importing countries before any shipment occurs.[85] Although the federal RCRA also prohibits exporting hazardous waste without prior informed consent from the receiving nation, there is significant ambiguity on the level of information required to be disclosed to said nation.[86] Compounded with the fact that the US has repeatedly failed to ratify the treaty that would put RCRA into alignment with the Basel Convention, this legislative standstill reflects a deeper political debate about national sovereignty and the extent to which international environmental agreements should shape domestic waste policy. These factors have essentially left the United States outside of the Convention's regulatory framework, reinforcing the fragmented and inconsistent approach to electronic waste management that characterizes current U.S. policy.

3. EPR

Returning to a look at state policy, many of the existing state laws regarding used electronics are based on the concept of extended producer responsibility (EPR). EPR is a policy approach emphasizing the accountability of the producer to follow products along the entire lifecycle, including at the post-consumer stage. These policies strive to reduce waste and lower public spending on waste management. An EPR policy is characterized by the shifting of responsibility (physically and/or economically; fully or partially) upstream to producers; and the provision of incentives to producers to take into account environmental considerations when designing their products.[87]

EPR systems can be thought of as a mandatory application of product stewardship, allowing for better monitoring and enforcement of electronics recycling. These systems no longer rely on consumers to pay for collection and processing of recycled material and instead require companies to take on that burden. A key component of EPR policy is eco-modulation,

---

[85] Basel Convention. "Basel Convention > Implementation > Controlling Transboundary Movements > Overview." Copyright 2011 by Basel Convention, n.d. https://www.basel.int/Implementation/Controllingtransboundarymovements/Overview/tabid/4325/Default.aspx.

[86] Nakagawa, Melanie. "Overview of Prior Informed Consent from and International Perspective." *Sustainable Development Law & Policy* 4, no. 2 (January 1, 2010): 4. https://digitalcommons.wcl.american.edu/sdlp/vol4/iss2/4.

[87] Laubinger, Frithjof, Andrew Brown, Maarten Dubois, and Peter Börkey. "Modulated Fees for Extended Producer Responsibility Schemes (EPR)." *OECD Environment Working Papers*, October 30, 2021. https://doi.org/10.1787/2a42f54b-en.

which aims to incentivize sustainable product design to reduce environmental harm.[88] This is done through establishing fee structures which can take a few different forms, either through fixed rates or a variable rate depending on product type and volume sold in the state. Eco-modulation is a part of most EPR laws, however the actual structure of fees varies by legislation.

The previously mentioned state operated recycling program in Washington is an example of an EPR regulation. Maine offers a further illustration of this approach, adopting an EPR law with a broader scope of covered products, including 3D printers, game consoles, and virtual reality headsets. Similarly, producers must pay based on net amount and recyclability of their products. The resulting funds are allocated to municipalities, which are responsible for ensuring adequate collection opportunities for their residents, coordinating with state-approved consolidators to collect materials and invoice manufacturers for their share of materials. Manufacturers must register with the department of environmental protection and pay an annual fee; while retailers can only sell products of manufacturers in compliance with the law.[89]

While EPR laws promote the importance of recycling and continue to adapt to new product developments, there are still legislative shortcomings that can be improved upon. As mentioned above, due to the lack of harmony among state legislation, EPR laws also vary greatly in the type of devices covered in each state, meaning there is no unified performance goal for effective recycling. These laws also fail to incentivize the end of producing difficult-to-recycle goods, especially since most manufacturers are seeking a weight target for recycling, rather than prioritizing reusability. This perpetuates the idea that products have reached their end-of-life and will ultimately be disposed of.

Below, we propose an expanded version of EPR that mends fractured legislation and includes a higher level of liability for following electronic materials through its life cycle of repair and reuse.

---

[88] Pierce, Lucy and SPC's Packaging EPR Collaborative. "EPR: Eco-Modulation Overview." Edited by Olga Kachook, Brad Kurzynowski, Paula Leardini, and Sheila Anzures, March 2025. https://sustainablepackaging.org/wp-content/uploads/2025/04/SPC-Mini-EPR-Eco-Modulation-Final.pdf.

[89] National Conference of State Legislatures. "Extended Producer Responsibility Report," 2023. https://documents.ncsl.org/wwwncsl/Environment/Extended-Producer-Responsibility-f01.pdf.

Electronic Product Recovery and Recycling (EPR2)

I. EPR2 Framework Overview

Considering the importance of a shift towards used electronic reprocessing (UER), the fragmented regulatory landscape within the United States, and the economic barriers to domestic recycling, we propose an expanded framework to replace the current model of Extended Producer Responsibility (EPR), in which producers are held liable for their products along the entire lifecycle. Electronic Product Recovery and Recycling (EPR2) expands the scope of responsibility to provide concrete performance incentives tied to repairability, product longevity, and material recovery yields rather than weight recycled. EPR2 recognizes the value of existing transnational reuse and materials recovery networks, and incorporates fair-trade partnerships with global refurbishers and recovery facilities as opposed to attempting to internalize the entire system domestically.

A central feature of EPR2 is the establishment of a unified federal framework, rather than the current patchwork of state-level regulations. A national system would require producers to report recovery rates and product design characteristics to a single coordinating body to ensure consistent definitions, data formats, and reporting requirements across states. Harmonization would reduce administrative burdens for producers operating nationwide, lower compliance costs for recyclers, and allow for more accurate tracking of material flows.[90] It would also prevent double-counting of recovered materials, which occurs when the same reuse or recycled product is reported separately in multiple jurisdictions due to inconsistent reporting boundaries. Finally, a unified framework would strengthen the coordination between federal and state agencies, making it possible to link domestic recycling networks with certified global partnerships under a shared regulatory system.

A fully domestic recycling model is not particularly feasible on its own without significant capital investment in scalable advanced recovery facilities and workforce development, along with stronger domestic secondary markets capable of absorbing refurbished

---

[90] Robin Ingenthron, "Why We Should Ship Our Electronic "Waste" to China and Africa," VICE, July 30, 2024, https://www.vice.com/en/article/e-waste-recycling-exports-are-good/.
"Extended Producer Responsibility and Economic Instruments," OECD, 2024, https://www.oecd.org/en/topics/sub-issues/extended-producer-responsibility-and-economic-instruments.html#:~:text=Extended%20producer%20responsibility%20is%20a,goals%20such%20as%20recycling%20targets.

electronics and reprocessing recovered materials. The United States lacks sufficient capacity to process its full electronic material stream, while informal and semi-formal recovery economies already operating across West Africa, Southeast Asia, and Latin America sustain highly skilled repair and refurbishment labor networks. Globally, an estimated 20 million informal waste workers participate in material collection and repair.[91] In West Africa alone, thousands of workers participate in these informal, yet highly organized economies.[92] These activities extend product lifespans, recover material value that would otherwise be destroyed, and make devices accessible to households and businesses that might otherwise be excluded from digital access. Furthermore, even if the U.S. developed the capacity to repair and recover 100 percent of its electronic material stream, there would still be limited domestic pathways to reintroduce those materials back into circulation.[93]

Circularity requires both recovery capacity and reuse pathways, both of which exist in global refurbishment and recovery economies that EPR2 seeks to recognize, support, and regulate fair-trade partnerships.

II. Shifting Performance Metrics Toward Reuse and Recovery

Most existing EPR systems measure performance by weight-based recycling targets, which do not distinguish between devices that are kept in use through reuse or repair and devices that are mechanically shredded, even when components could be recovered.[94] Current targets do not incentivize designing products for longevity or to support reuse and material recovery. EPR2 would introduce performance metrics that prioritize keeping products in use for as long as possible.

Under this approach, verified reuse–such as refurbished devices resold, donated, or redeployed into secondary markets–would count toward producer compliance obligations. Devices that cannot be repaired would still qualify for compliance credit based on the proportion of components and metals recovered for reprocessing rather than simply the total weight recycled. Recovery networks would be required to follow the EU waste hierarchy, in which preparing for reuse is prioritized first, followed by recovery of components and materials for

91 "Extended Producer Responsibility: Basic Facts and Key Principles."
92 Adu and Baffour Awuah, "Towards a Circular Economy: E-Waste Management in Africa."
93 U.S. Government Accountability Office, "Science & Tech Spotlight: Consumer Electronics Recycling."
94 "Extended Producer Responsibility: Basic Facts and Key Principles."

reprocessing, and lastly, disposal, as the least desirable.[95] Reorienting performance metrics toward reuse and material recovery also requires strengthening the networks where these activities are already occurring.

III. Cross-Border Recovery Partnerships and Fee Allocation

Under EPR2, producers could meet part of their collection and recovery obligations by partnering with certified refurbishers and reuse markets abroad. Robin Ingenthron, founder of World Reuse, Repair, and Recycling Association (preponderantly referred to as Fair Trade Recycling), argues that exporting tested and properly classified electronic materials to skilled refurbishment and recovery network would give technicians in developing markets access to high quality inputs, drive out exporters who ship unsorted scrap, and increase leverage to improve labor and environmental standards at receiving facilities–while also lowering U.S. e-recycling costs and improving trade balance. This would provide a steady and reliable supply of both repairable devices and non-repairable units with recoverable materials, giving receiving facilities the stability needed to specialize, plan, and invest in better diagnostic and refining techniques.[96] Much like fair trade coffee, where pricing stability and cooperative governance enable farmers to invest in better equipment and processing, a fair trade electronics system would ensure that refurbishers and materials recovery facilities have predictable supply and transparent contracts. When importers can rely on receiving unmarred electronic materials, they are able to plan around stable supply, invest in appropriate sorting and diagnostic tools, and run recovery processes that are safer and more efficient, rather than resorting to informal or hazardous practices associated with "sham recycling."[97]

Over time, these partnerships could create mutually reinforcing accountability loops, in which exporters improve testing and quality control to maintain certification, and certified receiving facilities would be better positioned to adopt cleaner and more standardized recovery practices. EPR2 would formalize this arrangement by developing certification criteria modeled on existing fair-trade and ISO (International Organization for Standardization) frameworks,

---

[95] European Union, "Waste Hierarchy," EUR-Lex, n.d., https://eur-lex.europa.eu/EN/legal-content/glossary/waste-hierarchy.html.
[96] Ingenthron, "Why We Should Ship Our Electronic "Waste" to China and Africa."
[97] ibid.

requiring disclosure of export destinations, and ensuring that partners meet agreed upon labor and environmental standards.

In the longer term, EPR2 could also enable cross-border fee allocation, where a portion of producer compliance fees follows exported products to support safe, skilled recovery infrastructure in the receiving country. This would not be a charity model, since altruism alone has not been sufficient to drive systemic change in this sector. Instead, exporters would pay a tiered compliance fee linked to the condition of the exported material and the certification of the receiving facility. The fee would be linked to a clear classification system requiring exporters to document whether a shipment contains reusable equipment, repairable devices, or units designated for materials recovery. This documentation would help resolve long standing ambiguity over which exports fall under hazardous waste controls.

Fees collected at the point of sale would continue to support domestic collection programs, consumer education, and state and municipal recycling systems. However, when materials are legally exported to certified refurbishers or recovery plants, a designated share of the compliance fee would accompany the shipment, supporting training, safer processing methods, and research and development focused on increasing the yield and efficiency of recovering metals and components from non-repairable devices. Producers could reduce their required fee by documenting the collection and proper handling of discarded electronics. Companies that collect their own products would face a lower fee, and companies that collect additional electronic materials beyond their own brands could qualify for no fee.

Under this tiered structure, exporters that consistently screen materials and maintain long-term partnerships with certified refurbishers and recovery facilities naturally fall into the lowest-fee categories, and companies that externalize risk or ship mixed, poorly screened loads fall into the highest-fee category. While cross-border recovery partnerships establish reliable pathways for reuse and recovery, their effectiveness depends on devices being designed in ways that allow reuse and material recovery. EPR2 therefore also shifts incentives upstream to ensure that products can be reused, repaired, and disassembled for material recovery at the end of their lifespan.

IV. Eco-Modulated Fees that Incentivize Better Product Design

The OECD reports that while "eco-modulated fees"--a regulatory approach where producer responsibility fees are adjusted based on a product's environmental impact–have begun to appear in policy frameworks in the European Union (EU), they are limited in scope and too weak to drive major product redesign.[98] In most existing EPR systems, producers pay a flat fee per unit or per weight, regardless of whether a device is durable, modular, or repairable, leaving no financial incentive to extend product lifespan.

To address this, EPR2 would implement advanced eco-modulated fees tied to measurable design performance metrics. Lower fees would apply to devices that are modular, designed for disassembly, and built with components (such as batteries and screens) that meet EU durability benchmarks, such as maintaining performance for 800+ charge cycles and having replacement parts available for 5-7 years.[99] Higher fees would apply to products with sealed components, non-replaceable batteries, operating systems designed to expire before the hardware fails, or deliberate obsolescence. Fee criteria could draw on standardized tools such as the EU Repairability Index, which evaluates ease of disassembly, spare parts availability, and access to repair information. The resulting fees, paid by producers, would fund the maintenance of a public repairability database that details disassembly procedures and supports device audits to ensure repairability standards are consistently met.

V. Toward a Circular Electronics Economy

Taken together, these reforms reposition discarded electronics as materials that still hold value, rather than waste that needs to be moved out of sight. EPR2 realigns incentives across the lifespan of a device. Producers are pushed to design products that can be repaired and disassembled. Recovery networks are encouraged to prioritize reuse and the recovery of components and materials rather than simply processing volume. Cross-border partnerships recognize and support the skilled refurbishment and recovery economies that already play a central role in keeping electronics in circulation. By replacing weight-based recycling quotas with performance standards based on repair, reuse, and material recovery, and by connecting

---

[98] "Extended Producer Responsibility and Economic Instruments."

[99] European Commission, "Commission Regulation (EU) 2023/1670 on Ecodesign Requirements," *EUR-Lex* (Official Journal of the European Union, August 31, 2023), https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32023R1670.

domestic collection to certified global recovery networks, EPR2 shifts U.S. electronics policy from a linear disposal model toward a circular system in which electronic goods remain active resources.

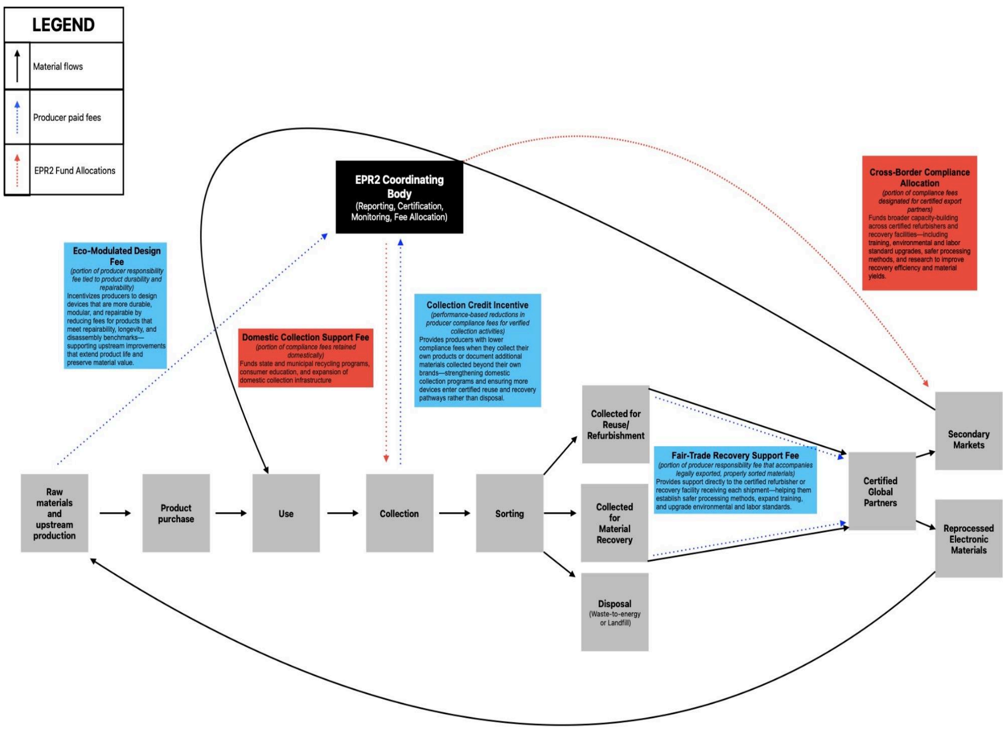


Figure 3: Conceptual model of the EPR2 framework illustrating material flows, producer-paid fees, and fund allocations across the electronics lifecycle as a pathway toward a Circular Electronics Economy.

Our proposed EPR2 framework aims to reignite value and care into electronics that are overlooked and disposed of due to their used status. This expanded vision of EPR reinstates the necessity of following an electronic device through its entire lifespan, advocating for further reuse and repair past its planned "end of life." Throughout this paper, we explain the harmful connotations of framing used electronics as "waste," consequences of traditional mining and extraction techniques, and the structural and economic barriers to domestic recycling in efforts to call for a cohesive, global approach towards incentivizing repairability, product longevity, and material recovery. It's important to recognize the effectiveness of a unified network spanning across national borders, no longer focusing solely on domestic processing and disposal. As one of the biggest generators of used electronic material, the U.S. lacks the ability to process its entire material stream; and it doesn't need to. One connected entity, composed of global cooperation and partnerships, eliminates ambiguity on labeling and categorizing used electronics which increases efficiency in processing these materials, and preserves environmental integrity on a larger scale.

References

Adu, Frank, and George Baffour Awuah. "Towards a Circular Economy: E-waste Management in Africa." African Center for Economic Transformation, May 12, 2025. https://acetforafrica.org/research-and-analysis/reports-studies/reports/towards-a-circular-economy-e-waste-management-in-africa/.

Aggregates Equipment, Inc. "The Challenges of E-Waste Recycling." AEI Screens, June 3, 2025. https://aeiscreens.com/news/the-challenges-of-e-waste-recycling/.

Azam, Shahid, and Qiren Li. "Tailings Dam Failures: A Review of the Last One Hundred Years." Geotechnical News, December 2010. https://ksmproject.com/wp-content/uploads/2017/08/Tailings-Dam-Failures-Last-100-years-Azam2010.pdf.

Basel Convention. "Basel Convention > the Convention > Overview." Copyright 2011 by Basel Convention, n.d. https://www.basel.int/theconvention/overview/tabid/1271/default.aspx.

Basel Convention. "Basel Convention > Implementation > Controlling Transboundary Movements > Overview." Copyright 2011 by Basel Convention, n.d. https://www.basel.int/Implementation/Controllingtransboundarymovements/Overview/tabid/4325/Default.aspx.

Campbell, Katie, and Ken Christensen. "Where Does America's E-waste End up? GPS Tracker Tells All." PBS News, May 10, 2016. https://www.pbs.org/newshour/science/america-e-waste-gps-tracker-tells-all-earthfix#ref2

Desonie, Dana, PhD. "Environmental Impacts of Mining." CK-12 Foundation, December 2, 2025. https://flexbooks.ck12.org/cbook/ck-12-middle-school-earth-science-flexbook-2.0/section/21.6/related/rwa/the-berkeley-pit/.

Henny, Charles J., Robert J. Hallock, and Elwood F. Hill. "Cyanide and Migratory Birds at Gold Mines in Nevada, USA." Ecotoxicology 3, no. 1 (March 1, 1994): 45–58. https://doi.org/10.1007/bf00121387.

Julia Corwin, "The Hidden Environmental Labour of Electronics Repair," The London School of

Economics and Political Science, January 28, 2025, https://www.lse.ac.uk/research/research-for-the-world/sustainability/environment-electronics-repair.

Department of Justice. "Second Largest U.S. Copper Producer Implements Comprehensive Cleanup at Bingham Canyon Mine in Utah," July 9, 2007. https://www.justice.gov/archive/opa/pr/2007/July/07_enrd_488.html.

Diment, Dmitry. "Electronic Goods Recycling in the US - Market Research Report (2015-2030)." IBISWorld, August 2025. https://www.ibisworld.com/united-states/industry/electronic-goods-recycling/4510/.

Directory, Sustainability. "Urban Mining Practices → Term." Energy → Sustainability Directory, December 2, 2025. https://energy.sustainability-directory.com/term/urban-mining-practices/.

Du Plessis, C.A., H. Lambert, R.S. Gärtner, K. Ingram, W. Slabbert, and J.J. Eksteen. "Lime Use in Gold Processing – a Review." Minerals Engineering 174 (October 27, 2021): 107231. https://doi.org/10.1016/j.mineng.2021.107231.

Earthworks. "Earthworks Factsheet Problems with Bingham Canyon Mine." Earthworks Factsheet. Earthworks, 2006. https://earthworks.org/wp-content/uploads/2021/09/FS_Problems_BinghamCanyon_2011low.pdf.

Earthworks. "Cyanide Use in Gold Mining - Earthworks." Earthworks, June 11, 2022. https://earthworks.org/issues/cyanide/.

Emerman, Steven H. and Malach Consulting. "Causes and Consequences of the Failure of the Tailings Dam at the Agroindustrial El Corazón Gold Mine on November 4, 2023, Imbabura Province, Northern Ecuador," 2024. https://earthworks.org/wp-content/uploads/2025/03/El_Corazon_Report_Emerman.pdf.

ERI. "Indiana State E-Waste Legislation - ERI," June 30, 2025. https://eridirect.com/sustainability/us-legislation/indiana/.

ERI. "Minnesota State E-Waste Legislation - ERI," June 30, 2025. https://eridirect.com/sustainability/us-legislation/minnesota/.

European Commission. "Commission Regulation (EU) 2023/1670 on Ecodesign Requirements." *EUR-Lex*. Official Journal of the European Union, August 31, 2023. https://eur-lex.europa.eu/legal-content/EN/ALL/?uri=CELEX:32023R1670.

European Union. "Waste Hierarchy." EUR-Lex, n.d. https://eur-lex.europa.eu/EN/legal-content/glossary/waste-hierarchy.html.

OECD. "Extended Producer Responsibility and Economic Instruments," 2024. https://www.oecd.org/en/topics/sub-issues/extended-producer-responsibility-and-economic-instruments.html#:~:text=Extended%20producer%20responsibility%20is%20a,goals%20such%20as%20recycling%20targets.

"Extended Producer Responsibility: Basic Facts and Key Principles." *OECD Environment Policy Papers No. 41*. Organisation for Economic Co-operation and Development, April 2024. https://www.oecd.org/content/dam/oecd/en/publications/reports/2024/04/extended-producer-responsibility_4274765d/67587b0b-en.pdf.

Fornalczyk, A., J. Willner, K. Francuz, and J. Cebulski. "E-waste as a Source of Valuable Metals." *Archives of Materials Science and Engineering*. Vol. 63, October 2013. http://www.amse.acmsse.h2.pl/vol63_2/6325.pdf.

Forti, Vanessa, C.P. Baldé, Ruediger Kuehr, and Garam Bel. "The Global E-waste Monitor: Quantities, Flows, and the Circular Economy Potential." Report. Bonn, Germany: United Nations University/UNITAR SCYCLE Programme, 2020. https://www.itu.int/en/ITU-D/Environment/Documents/Toolbox/GEM_2020_def.pdf.

Hailer, M. Katie, Christopher P. Peck, Michael W. Calhoun, Robert F. West, Kyle J. James, and Steven D. Siciliano. "Assessing Human Metal Accumulations in an Urban Superfund Site." Environmental Toxicology and Pharmacology 54 (June 27, 2017): 112–19. https://doi.org/10.1016/j.etap.2017.06.001.

Hazelwood, Dylan A., and Michael G. Pecht. "Life Extension of Electronic Products: A Case Study of Smartphones." *IEEE Access* 9 (January 2021): 144726–39. https://doi.org/10.1109/access.2021.3121733.

Heinrich, Christoph A. "The Chain of Processes Forming Porphyry Copper Deposits—An Invited Paper." Economic Geology 119, no. 4 (June 1, 2024): 741–69. https://doi.org/10.5382/econgeo.5069.

Hoffmann, and James Edward. “Gold Processing | Refining, Smelting & Purifying.” Encyclopedia Britannica, July 26, 1999. https://www.britannica.com/technology/gold-processing/Mining-and-concentrating.

Ibrahim, Abu Bakri. “How Much E-waste Is Recycled in the US?” E-Waste Collection & Recycling Association, June 21, 2024. https://ewcra.org/2024/06/21/e-waste-recycled-in-us/.

IndustriALL. “What Are Tailings Dams?,” March 1, 2019. https://www.industriall-union.org/why-you-need-to-know-about-tailings-dams.

Ingenthron, Robin. “Why We Should Ship Our Electronic “Waste” to China and Africa.” VICE, July 30, 2024. https://www.vice.com/en/article/e-waste-recycling-exports-are-good/.

International Energy Agency. “Recycling of Critical Minerals.” International Energy Agency, 2024. https://www.iea.org/reports/recycling-of-critical-minerals/executive-summary.

Izydorczyk, Grzegorz, Katarzyna Mikula, Dawid Skrzypczak, Konstantinos Moustakas, Anna Witek-Krowiak, and Katarzyna Chojnacka. “Potential Environmental Pollution From Copper Metallurgy and Methods of Management.” Environmental Research 197 (March 20, 2021): 111050. https://doi.org/10.1016/j.envres.2021.111050.

Johnson, Craig A. “The Fate of Cyanide in Leach Wastes at Gold Mines: An Environmental Perspective.” Applied Geochemistry 57 (June 11, 2014): 194–205. https://doi.org/10.1016/j.apgeochem.2014.05.023.

Kelly, Alma. “Electronics Recycling and Disposal in Boston, MA.” eWaste Solutions, July 16, 2025. https://ewastesolutionsusa.com/electronics-recycling-boston/.

Laubinger, Frithjof, Andrew Brown, Maarten Dubois, and Peter Börkey. “Modulated Fees for Extended Producer Responsibility Schemes (EPR).” *OECD Environment Working Papers*, October 30, 2021. https://doi.org/10.1787/2a42f54b-en.

LeCain, Timothy. “Death in Butte’s Berkeley Pit: What 342 Dead Snow Geese Tell Us About the Nature of Humans.” Digital Commons @ Montana Tech, n.d. https://digitalcommons.mtech.edu/public_lectures_mtech/60/.

Lee, Janice, Nicole Voigt, Alexander Meyer Zum Felde, Timm Lux, Tian Feng, Anna Kipot, and Colin Barber. “Don’t Throw Away The Opportunity in E-Waste.” Boston Consulting

Group, June 26, 2023. https://www.bcg.com/publications/2023/seizing-opportunity-ewaste-recycling.

Liu, Kang, Quanyin Tan, Jiadong Yu, and Mengmeng Wang. “A Global Perspective on E-waste Recycling.” *Circular Economy* 2, no. 1 (February 24, 2023): 100028. https://doi.org/10.1016/j.cec.2023.100028.

Lupo, John F. “Liner System Design for Heap Leach Pads.” Geotextiles and Geomembranes 28, no. 2 (December 10, 2009): 163–73. https://doi.org/10.1016/j.geotexmem.2009.10.006

“Manufacturers - Washington State Department of Ecology,” n.d. https://ecology.wa.gov/regulations-permits/guidance-technical-assistance/electronics-ecycle-guidance-and-reports/manufacturers.

Meidl, Rachel. “Closing the Loop on the World’s Fastest-growing Waste Stream: Electronics.” *Baker Institute for Public Policy*, June 14, 2023. https://www.bakerinstitute.org/research/closing-loop-worlds-fastest-growing-waste-stream-electronics#_edn130.

“Ministry of Mines, Government of India, Home,” n.d. https://mines.gov.in/webportal/copper.

Nakagawa, Melanie. “Overview of Prior Informed Consent from and International Perspective.” *Sustainable Development Law & Policy* 4, no. 2 (January 1, 2010): 4. https://digitalcommons.wcl.american.edu/sdlp/vol4/iss2/4.

National Conference of State Legislatures. “Extended Producer Responsibility Report,” 2023. https://documents.ncsl.org/wwwncsl/Environment/Extended-Producer-Responsibility-f01.pdf.

“New Factory Extracting Gold From E-Waste Unveiled by the Royal Mint,” n.d. https://www.royalmint.com/aboutus/press-centre/new-factory-extracting-gold-from-e-waste-unveiled-by-the-royal-mint/.

Pierce, Lucy and SPC’s Packaging EPR Collaborative. “EPR: Eco-Modulation Overview.” Edited by Olga Kachook, Brad Kurzynowski, Paula Leardini, and Sheila Anzures, March 2025. https://sustainablepackaging.org/wp-content/uploads/2025/04/SPC-Mini-EPR-Eco-Modulation-Final.pdf.

"Precise E-Waste Sorting With Sesotec Systems - Sesotec GmbH," n.d. https://www.sesotec.com/en/applications/recycling/electronic-waste.

"Risks of Leaks and Seepage From Improper Heap Leach Pad Design," n.d. https://www.btlliners.com/risks-of-leaks-and-seepage-from-improper-heap-leach-pad-design.

Russell, Brad. "Porphyry and Epithermal Deposits: Formation, Exploration, and Economic Impact." Discovery Alert, April 4, 2025. https://discoveryalert.com.au/porphyry-and-epithermal-deposits-formation-exploration-and-economic-impact/.

Schumacher, Kelsea A., and Lawrence Agbemabiese. "E-waste Legislation in the US: An Analysis of the Disparate Design and Resulting Influence on Collection Rates Across States." *Journal of Environmental Planning and Management* 64, no. 6 (September 2, 2020): 1067–88. https://doi.org/10.1080/09640568.2020.1802237.

Soopramanien, Ravi, and Pamela Usta. "E-Waste: A Bigger Problem Than You Think | Stanford Law School." Stanford Law School, October 21, 2015. https://law.stanford.edu/2015/10/21/e-waste-bigger-problem-think/.

Theme, Education Zone Pro by Rara. "Berkeley Pit." Butte-Silver Bow Public Archives, December 16, 2020. https://buttearchives.org/berkeley-pit/.

The Oregon Group. "Global Copper Demand to Increase 70% by 2050, to More Than 50 Mt - the Oregon Group - Critical Minerals And." The Oregon Group - Investment Insights, November 5, 2024. https://theoregongroup.com/commodities/global-copper-demand-to-increase-70-by-2050-to-more-than-50-mt/.

United Nations Environment Programme and International Solid Waste Association. "Global Waste Management Outlook." United Nations Environment Programme, 2015. https://www.unep.org/resources/report/global-waste-management-outlook.

U.S. Environmental Protection Agency. "Electronics Waste Management in the United States Through 2009." U.S. Environmental Protection Agency, 2011. https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P100BKKL.PDF.

US EPA. “National Primary Drinking Water Regulations | US EPA,” December 1, 2025. https://www.epa.gov/ground-water-and-drinking-water/national-primary-drinking-water-regulations.

US EPA. “Regulatory Exclusions and Alternative Standards for the Recycling of Materials, Solid Wastes and Hazardous Wastes | US EPA,” September 25, 2025. https://www.epa.gov/hw/regulatory-exclusions-and-alternative-standards-recycling-materials-solid-wastes-and-hazardous.

US EPA. “Resource Conservation and Recovery Act (RCRA) Overview | US EPA,” September 5, 2025. https://www.epa.gov/rcra/resource-conservation-and-recovery-act-rcra-overview.

U.S. Government Accountability Office. “Science & Tech Spotlight: Consumer Electronics Recycling.” U.S. Government Accountability Office, August 2020. https://www.gao.gov/assets/gao-20-712sp.pdf.

Varshney, Shubham, Mikkel Lundås, Prabhugouda Siriyappagouder, Torstein Kristensen, and Pål A. Olsvik. “Ecotoxicological Assessment of Cu-rich Acid Mine Drainage of Sulitjelma Mine Using Zebrafish Larvae as an Animal Model.” Ecotoxicology and Environmental Safety 269 (December 7, 2023): 115796. https://doi.org/10.1016/j.ecoenv.2023.115796.

Vuppaladadiyam, Sai Sree Varsha, Bennet Sam Thomas, Chandan Kundu, Arun K. Vuppaladadiyam, Huabo Duan, and Sankar Bhattacharya. “Can E-waste Recycling Provide a Solution to the Scarcity of Rare Earth Metals? An Overview of E-waste Recycling Methods.” The Science of the Total Environment 924 (March 5, 2024): 171453. https://doi.org/10.1016/j.scitotenv.2024.171453.

“What Is e-Waste,” n.d. https://globalewaste.org/what-is-e-waste/.

Xu, Hailiang, Qiao Xu, Guankui Gao, Haitao Dou, Abdul Waheed, and Aishajiang Aili. “Advances in Ecological Restoration of Mining-Impacted Landscapes: Techniques, Case Studies, and Key Challenges.” Environmental Research 290 (December 5, 2025): 123485. https://doi.org/10.1016/j.envres.2025.123485.

Ylä-Mella, Jenni, Riitta L. Keiski, and Eva Pongrácz. “End-of-Use Vs. End-of-Life: When Do Consumer Electronics Become Waste?” *Resources* 11, no. 2 (February 7, 2022). https://doi.org/10.3390/resources11020018.

Yryszhan Zhakypbek et al., “Effects of Gold Mining on the Physicochemical Properties of Soils at the Akbakai Gold Deposit,” Engineered Science 36 (2025): 1670. https://dx.doi.org/10.30919/es1670