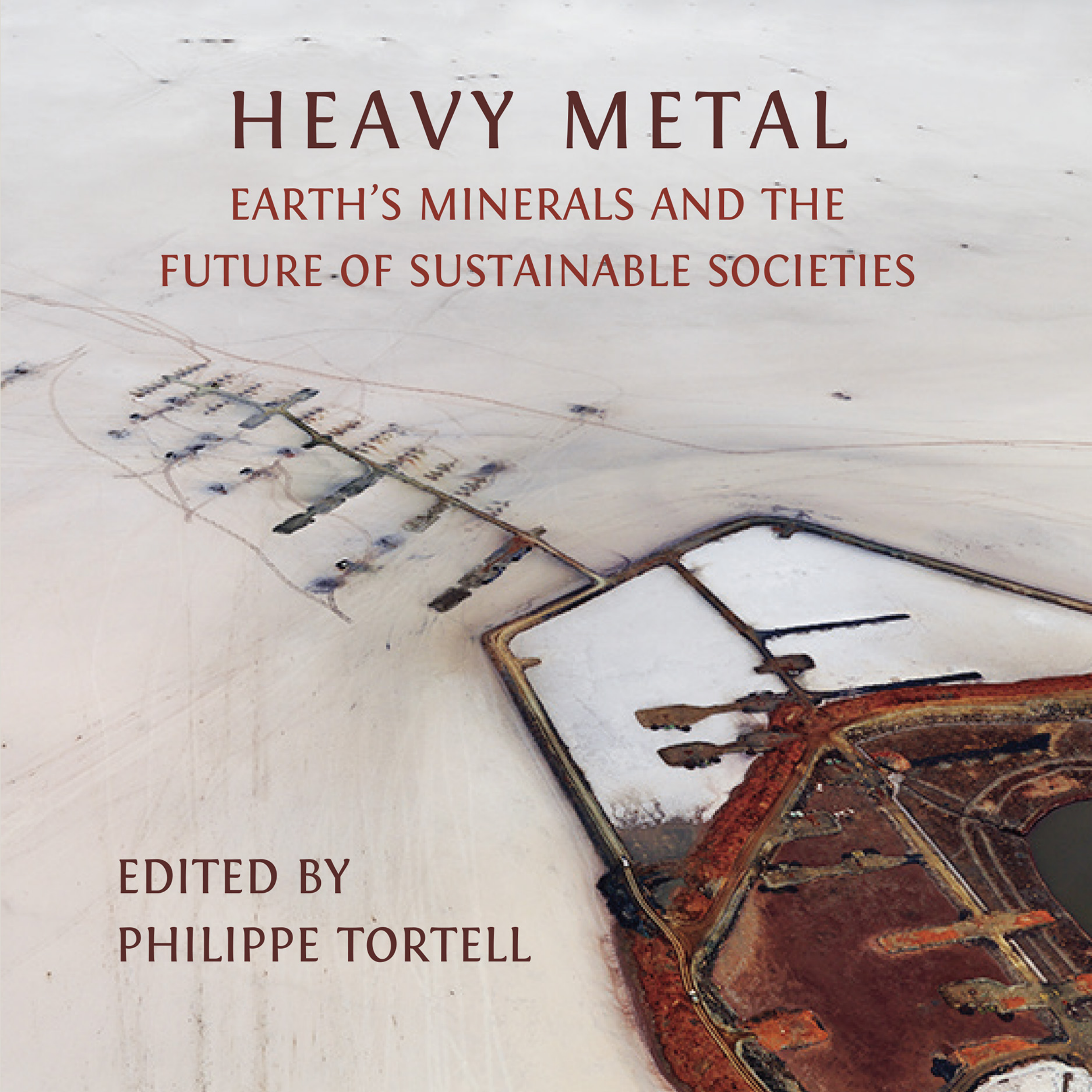

HEAVY METAL

EARTH'S MINERALS AND THE FUTURE OF SUSTAINABLE SOCIETIES

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A New Life for Old Metals

Maria Holuszko

In ancient human civilizations, metal objects were venerated in religious ceremonies, passed down across generations and traded as prized commodities. Today, thousands of years later, the situation is vastly different. As metals have become increasingly critical for the advancement of human societies—from cars and wind turbines to computers, smart phones and health care equipment—we have become increasingly disconnected from these vital elements. These days, you would be hard-pressed to name even a small fraction of the metals contained in your favorite electronic device. The average smartphone, for example, contains gold, silver, copper, lithium, platinum and a wide range of rare-earth elements (REEs) that most people have never even heard of—yttrium, lanthanum, terbium, neodymium, gadolinium and praseodymium, among others. We use these objects every day, often without much thought or intention, and we likewise dispose of them, sight unseen, without understanding where they go when they leave our hands, homes, schools and businesses. Many of these devices are produced with built-in obsolescence, designed to be used for just a short while, until something shinier and better comes along.

As global demand for critical metals grows rapidly with the expansion of renewable energy and digital economies, many difficult questions are being asked about how and from where projected mineral demands will be met. Some have called this a new 'gold

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rush', as countries around the world seek to secure strategically important mineral supplies for their future economic development.[1] But this time around, we will need much more than gold.

How are we to supply all these metals to support our future needs? In some cases, we have found substitutes for metals, most notably through the increasing use of plastics and other synthetic materials. But in many applications, such as electrical wiring, the unique properties of metals cannot (yet) be replicated by these materials, and the alternatives are not always cheaper or more environmentally friendly over the long term. Increased mining will be needed to supply growing metal demands, but this faces several significant challenges. For one thing, the decreasing metal grades of ore deposits are making it harder to extract economically viable quantities of metal from host rocks, while also increasing the amount of waste material that must be stored and treated, often for decades or longer.[2] At the same time, the potential negative social and environmental impacts of mining have created significant community opposition (and court challenges) to many new projects. And even for those mining projects that are conducted responsibly, with due attention to environmental, social and governance (ESG) issues, the extraction of minerals from Earth can never be sustainable in the true sense of the word. Once minerals are extracted from the ground, they can never be put back.

If we cannot replace the metals in our devices, homes and businesses, or mine our way out of the problem, the long-term solution will have to rest with the transition to a circular economy, where products (and their embedded metals) are recycled or 'upcycled' back into the industrial supply chain. The goal of this approach is to maintain mineral resources in circulation for as long as possible, while minimizing the need for primary resource extraction. To achieve this goal, we must be able to recover and reuse the materials found in our manufactured goods.

All metals, including copper, zinc, gold and the others, are chemical elements—the basic building blocks of matter. For the most part (ignoring radioactive decay and a few other processes), metals are neither destroyed or created on Earth; they can combine with other elements to form various compounds, but the chemical properties of the pure elements remain constant. This means that most of the metals that exist on Earth today have been here, unchanged, since the earliest days of our planet, continuously recycled across different geological reservoirs for more than four billion years. And at some distant point in the future, long after we are gone, all the metals on our planet (minus whatever we send into outer space) will continue to exist on Earth. Seen in this light, the problem of metal supply is not about the total quantity of metals on the planet, but rather about how they can be kept circulating in useful and accessible forms.

Before the Industrial Revolution, it would have been unthinkable to discard metallic objects, which were made by hand, often by skilled artisans. These objects were used for as long as possible, and then re-purposed into other items; swords were converted into ploughs, spears into hooks.[3] Since the time of the ancient Romans, when bronze coins were melted to produce raw material for statues and military equipment, metal recycling has increased at various points in history, particularly during times of scarcity and war. Following the Declaration of Independence, in 1776, American patriots in New York toppled a metal statue of Britain's King George III, melting it down to make musket balls for the Continental Army. About a century later, during the American Civil War, southerners facing a blockade of their ports began melting church bells and steeples, pots, pans and farm equipment to fuel their war effort. As they struggled against Abraham Lincoln's well-equipped northern armies, confederate soldiers collected spent ammunition from battlefields to replenish their metal supplies.

During the early twentieth century, metal recycling expanded rapidly with growing industrialization. The first aluminum recycling factories appeared in the United States by the early 1900s, shortly before the outbreak of World War I, when the US government initiated a nationwide metal recycling campaign. All citizens were encouraged to collect metal items, particularly tin, aluminum, copper and steel, which could be used to increase the production of tanks, ships and other weapons needed for mechanized warfare. About twenty years later, as the world found itself in another global conflict, recycling became critically important once again. At the beginning of World War II, there were more than one million tons of scrap metal scattered across farms in the US, enough to construct more than one hundred warships, thousands of tanks and airplanes, and countless bullets.

In the post-World War II years, the economic imperative for metal recycling diminished as military demands decreased, and plastics began to substitute metals in many products. But at the same time, a growing environmental consciousness emerged in the 1960s, focusing more attention on the contamination of land, water and air with various industrial wastes, including large amounts of abandoned metals. At the time of the first Earth Day, on 22 April 1970, only about half of the copper and 20% of the aluminum used in the US was recycled, adding to a growing problem of waste accumulation across the country. Today, half a century later, recycling has more firmly entered the public consciousness, but significant challenges remain. While Europe and South America now recycle more than 70% of their metals, this value is only about 45% in North America and Africa, leaving large amounts of potentially valuable material in waste streams.[4] In 2018, for example, US landfills received 10.5 million metric tons of steel, amounting to about 70%, by weight, of all material in municipal solid wastes. Clearly, we still have a long way to go to achieve a circular economy.

A significant part of our metal recycling challenges results from the growing complexity of metal-containing products. In the early twentieth century when recycling began at an industrial scale, metals were recovered in bulk forms from simple alloys—steel cars and tin cans, for example. Today, the nature of metal-containing products has changed significantly. Each year, millions of new electronic devices are introduced into the market to assist an increasingly digital lifestyle for consumers worldwide. These devices have increased productivity and access to information and entertainment, and they allowed us to stay connected during the global COVID-19 pandemic. The downside, however, is an accumulating mountain of waste scattered across our planet.

Electronic waste (e-waste) is now the fastest growing form of garbage on Earth, with over fifty million metric tons generated in 2020 alone, 7.3 kilograms of e-waste per person. This waste, equivalent to the mass of 5,000 Eiffel Towers, consists of a wide range of metal-containing products, from appliances, screens and monitors, lamps, and various IT and tele-communications equipment. The amount of e-waste generated correlates strongly with per capita gross domestic product (GDP), ranging from twelve to fifteen kilograms per person in North America, Europe and Australia, to four kilograms per person in Asia and two in Africa. And as the world grows richer (on average), more e-waste is being produced every year. Between 2014 to 2019, the global quantity of e-waste increased by 9.2 million metric tons, and by 2030, it is expected to reach about seventy-five metric tons, representing a doubling in less than two decades.[5]

The massive increase in the production of e-waste is far outpacing recycling rates. Currently, only about 15–20% of global e-waste is formally collected and appropriately recycled. The rest, more than 80% (about forty million metric tons in 2020), is either incinerated with other wastes, or dumped in landfills. As with e-waste production, recycling rates vary significant across the world; Europe has the highest rates at around 42%, followed by Asia, America and Australia (about 9–12%) and Africa, at less than 1%. Although infrastructure for e-waste recycling continues to improve in developed countries, a significant amount of e-waste is still illegally exported to developing nations, where recycling is mostly done informally, often using manual labor and methods that pose human health and environmental risks. Of particular concern is the presence of toxic metals in e-waste, such mercury, lead and cadmium, alongside potentially carcinogenic organic compounds used as flame retardants in various electronic devices.

Where some see a growing e-waste environmental catastrophe, others see significant economic opportunity. For one thing, e-waste is highly enriched in valuable metals, with concentrations that can be many times higher than the rocks from which they were initially extracted. Take gold for example; a rich geological deposit contains about five to ten grams of gold for every metric ton of rock excavated, as compared to about three hundred grams of gold in a metric ton of printed circuit boards (PCBs).[6] It is estimated that PCBs account for about 40% of the total monetary value of e-waste and could represent more than seven hundred million US dollars' worth of gold in Europe alone by 2025. Globally, the value of metals in all e-waste types (gold, silver, platinum, copper and others) was estimated to be more than fifty billion US dollars in 2019. For this reason, e-waste recycling could turn millions of metric tons of waste into billions of dollars of new wealth, while also addressing future metal supply gaps. And there are also a significant number of jobs that could be created in e-waste recycling. The Electronics TakeBack Coalition estimates that hundreds of thousands of people are currently employed in informal e-waste recycling, with over 500,000 jobs in the US alone, and possibly millions of additional jobs worldwide. Other important benefits from e-waste recycling relate to the lower environmental footprint of recycled metals, which require less energy and carbon dioxide (CO_2) emissions than an equivalent amount of metal obtained through primary extraction.

Given the potentially large economic and environmental benefits, why has more effort not gone into recovering important metals from our global e-waste scrap heap? As with many things, the devil is in the details. The process of recycling metals involves a series of distinct steps, which are often undertaken by different people, in locations spread out around the globe. An efficient recycling system requires that metal-containing scrap materials, including e-waste, are collected and separated from other waste streams, something that happens with varying degrees of efficiency around the world, and even within different regions of a single country. Collected e-waste must then be disassembled to remove potentially hazardous components and separate out different bulk materials (metal, plastic, glass). The sorted material is typically shredded, using various methods to separate metals, including magnets (for iron, steel and REEs) or gravity (copper, gold and silver). In recent years, new infrared and other optical sensors have also been used to selectively remove glass and plastics from metals, but these technologies can have high up-front costs, and are not well suited to smaller, informal operations, such as those that dominate recycling in developing countries.

A key challenge in e-waste recycling is the extent to which metals are increasingly embedded within composite materials containing ceramic, glass and various plastic polymers. Some of the materials within these composites are blended on a molecular scale, making the individual components invisible to the naked eye, and difficult to physically separate.[7] For such complex mixtures, other approaches are needed to recover metals, including pyrometallurgy, where materials are melted in a high-temperature furnace, and hydrometallurgy where wastes are treated with chemical solutions to extract dissolved metals. Both these approaches can be effective, but they each have drawbacks. Pyrometallurgy can extract significant amounts of metals from waste, but it has extremely high energy costs, and can release harmful compounds, such as dioxins, when plastics are burned. On the other hand, hydrometallurgy can be a rather slow and time-consuming process, and it requires aggressive 'leaching solutions'—including nitric, sulfuric and hydrochloric acids—that can pose significant environmental risks. Such risks must be factored into any cost-benefit analysis.

In recent years, there has been an increased emphasis on developing novel approaches to metal recovery from e-waste. One approach, inspired by nature, uses particular groups of microbes to extract metals from complex wastes.[8] This 'bioleaching' method holds significant promise as a more benign alternative to pyro- and hydrometallurgy, but it remains in its infancy, and has yet to be deployed at scale. Other high-tech approaches are also being developed. The tech giant, Apple, has built a robot named Daisy that can dismantle the company's iPhones and recover many of the valuable metals. A typical phone takes less than thirty seconds to process, and each robot can disassemble more than one million phones per year. That number is impressive, but it represents less than 1% of the new phones produced annually. A significant expansion of these technologies is thus needed, and other companies including Dell, Microsoft and Google have followed Apple's lead. They have come together to form the Circular Electronics Partnership, with the goal of significantly increasing recovery of metals and other valuable products from e-waste.

There is no doubt that technical innovation is needed. But that will not be enough. Innovative technologies will require appropriate regulatory and economic frameworks, with sufficient financing to operate at scale. The collection of e-waste needs to be significantly improved to provide an adequate 'feed stock' for new recycling methods. This could be achieved, for example, by building distributed networks bringing together informal e-waste collection and licensed recycling facilities, with appropriate financial incentives to attract experienced recyclers into the market. An increasing numbers of countries have legislation regulating the production and fate of e-wastes, but enforcement is poor in many cases, and existing policies do not sufficiently incentivize proper collection and management. Clear and enforceable regulations for e-waste collection and recycling are needed, with explicit responsibilities for the industry, consumers, municipalities and other levels of government.

Everyone has a role to play. Researchers must continue to develop more efficient, lower-cost and environmentally friendly technologies for e-waste recycling, seizing a significant opportunity to recover valuable materials from metal-rich 'urban mines'. Consumers should educate themselves on the full environmental and social impacts of their electronic products, demanding tighter oversight on e-waste disposal, and a licensing system to track the content of recycled materials (the electronic equivalent of fair-trade coffee, for example). The tech industry must take greater responsibility for its products, working to extend the lifetimes of our electronic gadgets, while also designing them for easier repair, upgrade and refurbishment. Both durability and ease of recycling should be built into the upstream design of all electronics, and manufacturers should also be actively involved in the downstream recovery process. Governments can help raise broad awareness about the importance of recycling, while also holding tech companies accountable, through both financial carrots and regulatory sticks. Governments at all levels, municipal, regional and national, should also work to standardize and streamline collection and recycling practices across different jurisdictions. In British Columbia, Canada, for example, recyclers only conduct the first steps of dismantling electronics before sending them by truck across the country to Quebec or Ontario for further processing. This represents a significant cost of both money and greenhouse gases, and a missed opportunity for local economic development and employment.

Looking ahead, we must work towards a global system that can recycle all metals currently in circulation, decoupling future economic growth from the large-scale extraction of primary resources. In this herculean task, we must focus on maximizing the use of our products over an extended lifetime, while also planning for their end-of-life recovery. Any future recycling systems will need to be practically feasible, cost effective and environmentally benign. They will also require appropriate financial incentives and enforceable regulatory frameworks. In the future, recycling of e-wastes will become increasingly attractive, as the cost of materials and waste disposal increases, and as the consumers become more aware of the true environmental footprint of their electronic devices. As we seek to live sustainably on a finite planet, we must come to once again appreciate the true value of the metals that support our daily lives.

Endnotes

1 See also 'The Future Demand and Supply of Critical Minerals' by Werner Antweiler in this volume.

2 See also 'Mine Waste' by Roger Beckie in this volume.

3 'A Review of: "The Recycling of Non-Ferrous Metals (1996)", Michael Henstock, The International Council on Metals and the Environment, Ottawa', I*nternational Journal of Surface Mining and Reclamation* 10.3 (2007): iv, https://doi.org/10.1080/09208119608964811

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8 See also ‘Microbial Mining’ by Gordon Southam in this volume.