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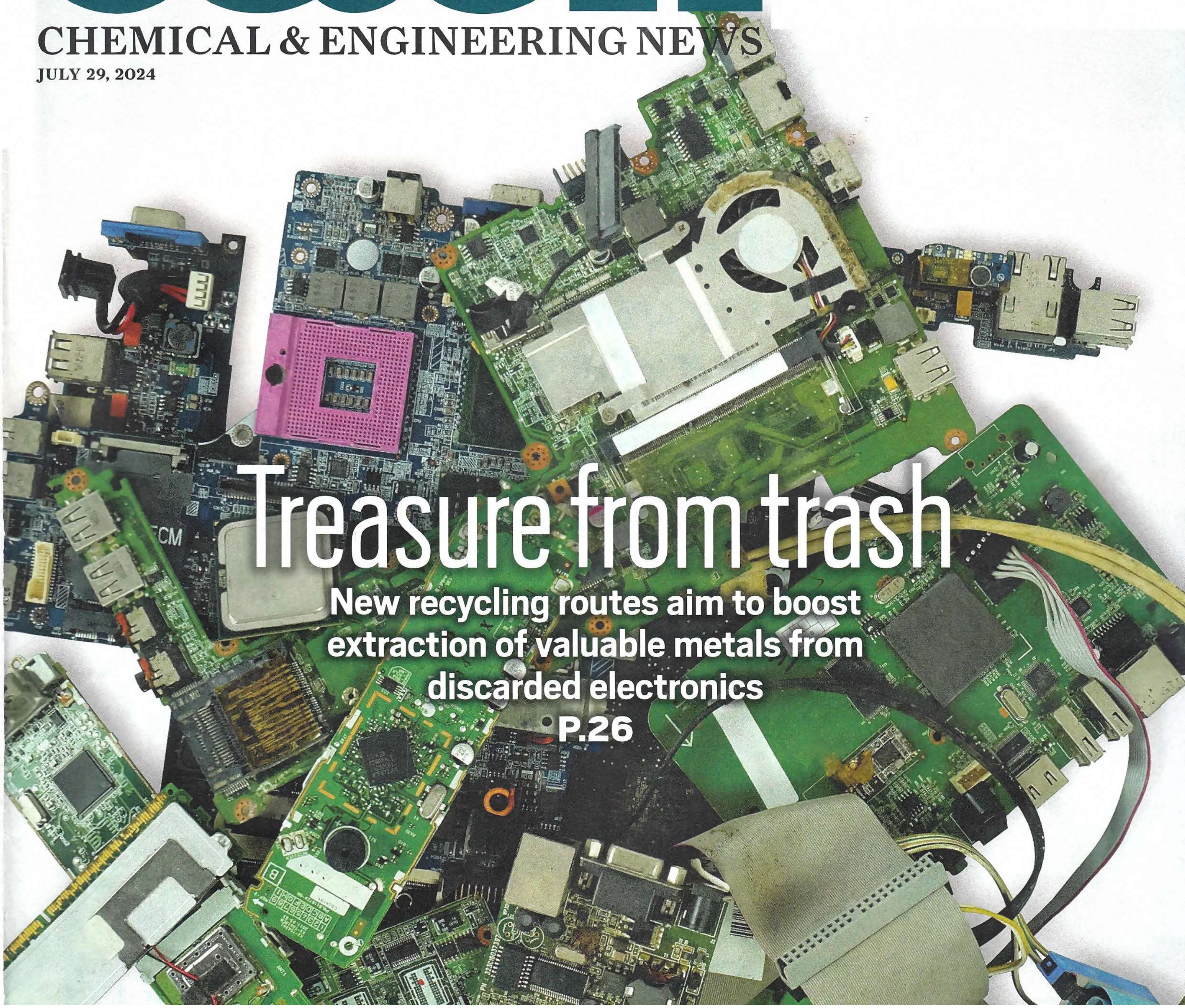

Treasure from trash

New recycling routes aim to boost extraction of valuable metals from discarded electronics

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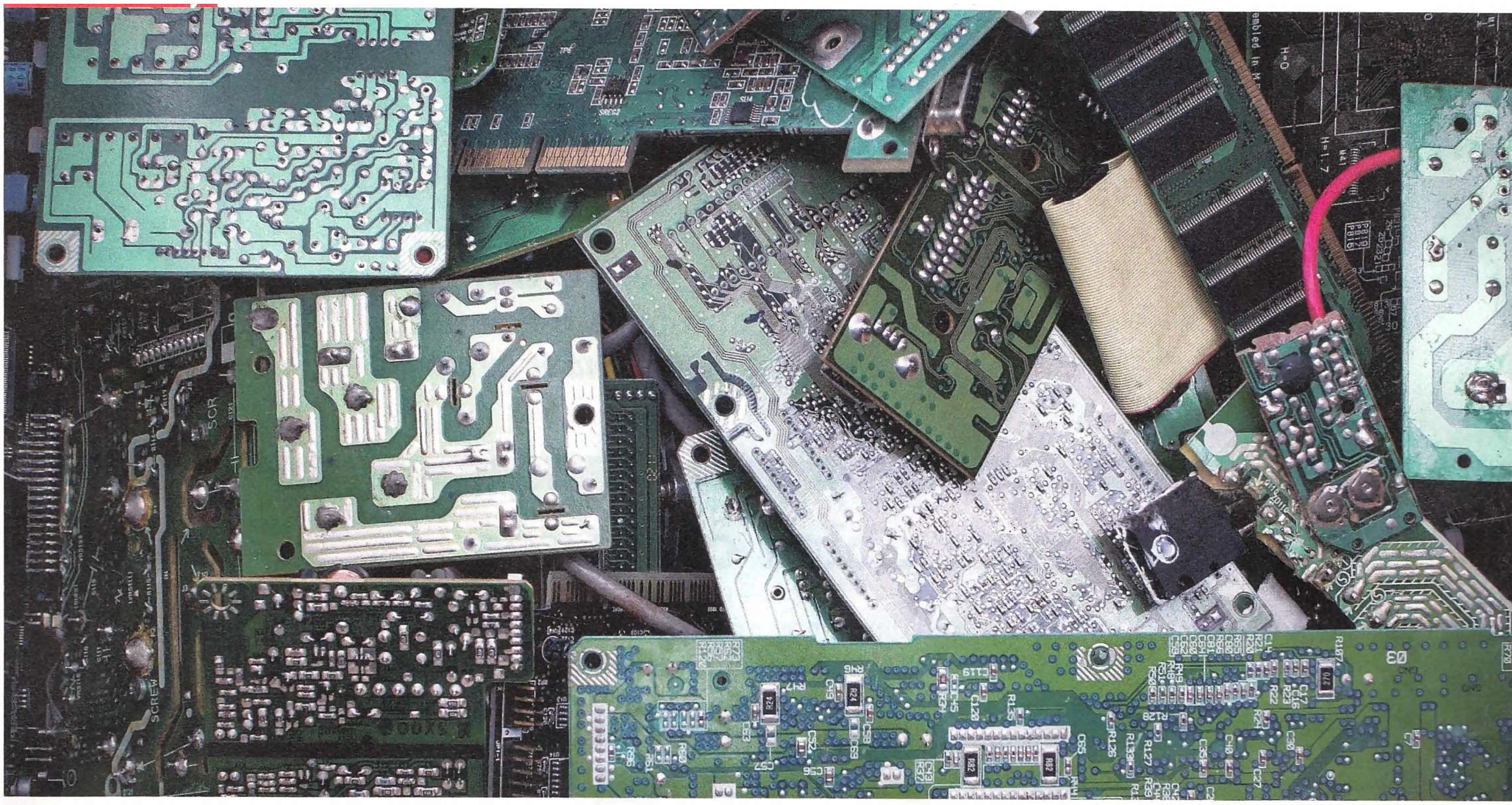

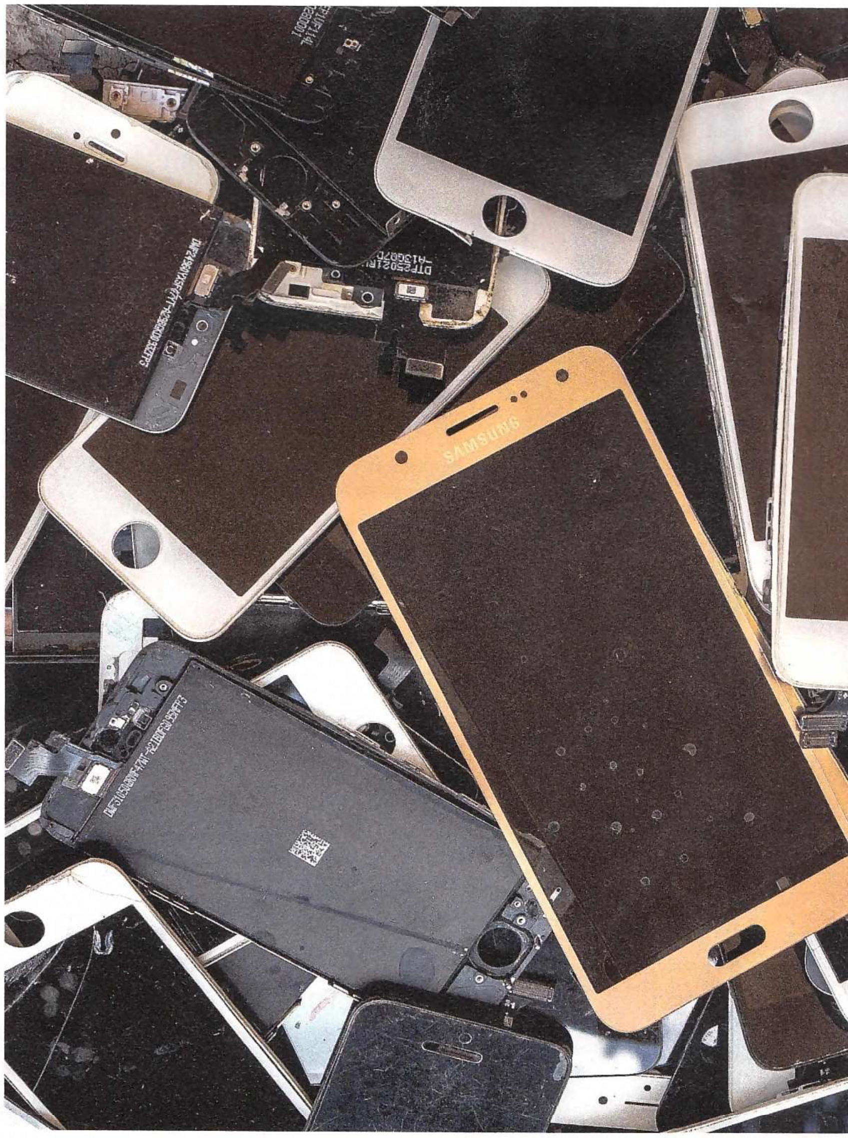
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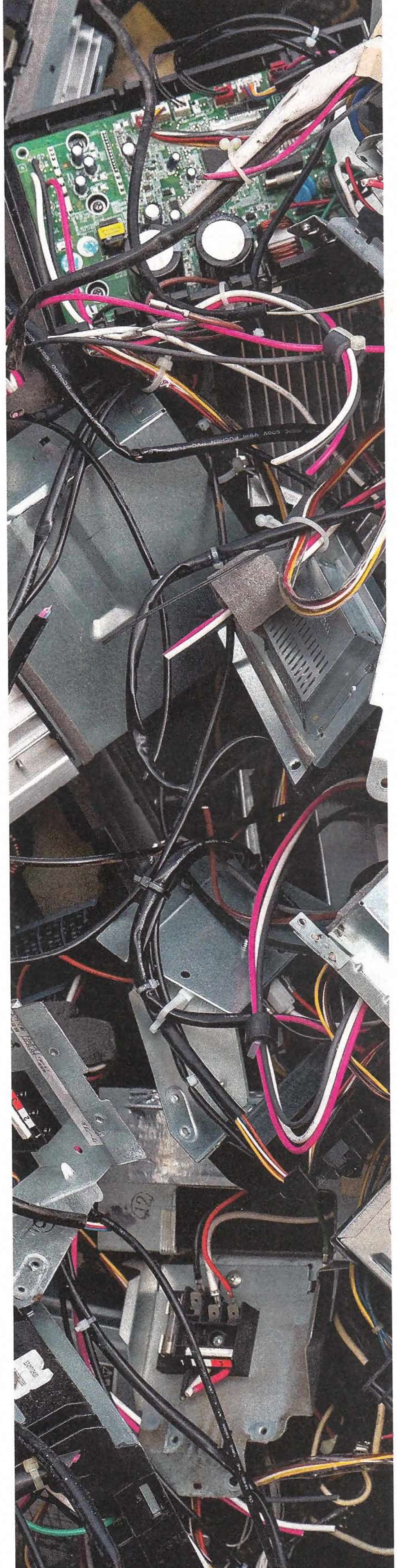

Electronic waste is a gold mine. How can we tap it?

Start-ups are seeking efficient, sustainable ways to recover billions of dollars' worth of valuable metals lost in e-waste

PRACHI PATEL, C&EN STAFF

In the dark corners of your attic shelves or the depths of your desk drawers likely sits a collection of defunct laptops, cameras, and gaming consoles. The phone you may be reading this on will probably join that junk pile once it becomes obsolete or its screen cracks.

The average person in the US threw away 21 kg of electronics in 2022, while the average person in Norway—the country with the highest per-capita e-waste—threw away 27 kg. Those numbers are close to the weight range of a pit bull, and the numbers add up. Globally, people discarded a record 62 million metric tons (t) of electronics, according to the United Nations' recent *Global E-waste Monitor 2024* report. That's the weight of over 1.7 million fully loaded semitrailer trucks, which, if lined up bumper to bumper, would reach almost around the equator.

And that trash contains treasure. Metals made up half the world's electronic trash, or e-waste, in 2022 and were worth $91 billion. Copper, iron, and gold accounted for a big chunk of that value. E-waste also contains aluminum, platinum, and rare earth elements such as neodymium, which are critical for the batteries and wind turbines needed to transition the world to green energy.

Mining these metals destroys habitats, pollutes soil and water, produces heaps of waste, and is

In brief

The world is drowning in electronic waste. The flood of e-waste we generated in 2022 contained $91 billion worth of valuable metals, according to a recent United Nations report. Almost 40% of those metals ended up in a landfill, were burned in incinerators, or were disposed of in uncontrolled ways. A mere 4% of some metals essential for clean energy were recovered from e-waste. Mining these same metals, as well as improperly recycling used electronics, causes pollution and human health hazards. Current recycling processes require high temperatures and harsh chemicals. Several researchers and companies are advancing economical, sustainable methods to recover more key metals from e-waste. These approaches could help facilitate a secure, circular supply of these materials.

linked to human rights abuses. Plus, the global supply of some metals is geopolitically shaky. Using urban mining—the recovery of materials from waste—to reclaim valuable metals from e-waste would alleviate these issues. It would enable the circular use of materials and help meet demand for critical metals. It would also prevent the emission of 52 million t of mining-related greenhouse gases.

"There are many benefits of recovered raw materials. It's much broader than carbon footprint," says Kees Baldé, senior scientific specialist at the UN Institute for Training and Research and lead author of the report. "That is the reason we must recycle every gram of gold and neodymium that is in e-waste."

But the world properly recycled less than a quarter of e-waste, according to the report. Most waste ended up being informally recovered at unregulated facilities or burned in the open, which squanders materials and spews toxic material such as mercury and flame retardants. Roughly another quarter went to landfills. Amid all this e-waste handling, almost 40% of the 31 million t of metals in the waste was simply not recovered, the report says.

Why is the world squandering so much valuable material? Poor waste management, a lack of regulation, and consumer and tech company behavior are mostly to blame.

A lack of good technology is a problem too, however. Innovative ways to recover more metals for lower cost and energy use will make recycling more lucrative, says Will Barker, CEO of the New Zealand–based start-up Mint Innovation. "Recycling has a low profit margin, and recyclers are looking for ways to improve their own bottom lines. Any technology enabling that by making recycling more efficient will ultimately increase recycling rates."

Mint and several other start-ups, various research groups, and even the Royal Mint in the UK are taking on the challenge of finding economically and environmentally sound ways to give valuable materials in e-waste a second life. Some teams are harnessing biology, while others are exploring mysterious new chemistries and employing electricity to dig into the e-waste gold mine.

A worker at start-up Mint Innovation's new commercial e-waste recycling facility in Sydney monitors the reactor carrying bacteria that extract gold from ground printed circuit boards.

Betting on biology

Truckloads of bags bursting with waste computer circuits roll up weekly to Mint Innovation's shiny new recycling plant just west of Sydney. Mint cut the ribbon at the plant in April. When running at full scale, the facility will use its biology-based process to recycle 3,000 t of the city's collected e-waste per year, recovering around 0.5 t of gold and 800 t of copper.

The start-up is focusing on printed circuit boards (PCBs), the plastic panels carrying electronics and wiring that are the heart of our gadgets. One t of PCBs contains at least 200 kg of copper, 0.4 kg of silver, and 0.09 kg of gold. The concentration of gold and other precious metals could be 10 times as high as that in natural ores, and these metals make up most of a spent PCB's value.

Yet only 20% of precious metals were recycled from e-waste, according to the UN report, in part because the cost of recovering them is too high to make fiscal sense. The recycling rate for copper was higher, at 60%, but still too low for a metal for which mining cannot keep up with the world's electrification needs.

E-waste's complexity hinders recycling. It includes phones and laptops, as well as e-cigarettes and microwave ovens—anything with a plug or a battery. A single smartphone may have over four dozen metals, some present in tiny concentrations. Video game consoles contain a different set of components than the ones in laptops. And even in a single type of product, materials may vary depending on the year and model. E-waste also contains hazardous materials, making recycling dangerous and expensive.

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> —**Will Barker,** CEO, Mint Innovation

Batteries, PCBs, and hard disk drives are major components of e-waste, and they contain high concentrations of valuable metals. Battery recycling has become economical and is growing rapidly because these energy storage devices contain substantial amounts of valuable cobalt and lithium. But that's not the case for PCBs and computer disk drives.

The small fraction of electronics that do get collected for recycling today are shipped to one of about a dozen smelters in Asia, Canada, and Europe. These large, energy-intensive facilities, which cost billions of dollars to build and operate, chop up the waste and either melt it at high temperatures to extract metals or leach it with harsh acids. The plastic that's left is often burned, used as fuel to heat the smelters. The smelting process works, but it generates carbon emissions and toxic by-products. "High-temperature processing creates no end of nasties that have to be scrubbed out," Barker says.

Mint says its biological process recycles PCBs with minimal cost, emissions, and waste. At its biorefinery, a hammer mill grinds PCBs into a sandy powder, which goes through an electroplating process to extract copper in the form of pure sheets. The remaining material goes to reactors containing bacteria that selectively take up gold. Then workers remove the biomass and heat, dry, and refine it, forming pure gold dust. The company uses mild reagents to leach silver, tin, and other valuable metals and finally sends the residue to partner firms to be repurposed into bricks and paving material.

The start-up's vision is to build a network of biorefineries in major cities around the world. Barker says Mint has plans to open a facility in the US soon. Avoiding shipping e-waste to smelters will lower cost and speed up turnaround times, increasing profit margins. "Most e-waste is produced in urban environments," he says. "We designed a plant that can be plugged into city infrastructure like power, water, and waste because the processing is clean and doesn't produce any nasties."

While Mint uses bacteria to grab gold, other teams are using microbes that hunger for rare earth elements. Rare earths, which include the 15 lanthanides as well as scandium and yttrium, are used to make the permanent magnets found in hard drives and smartphone speakers. Rare earths also play important roles in motors for wind turbines and electric vehicles. Despite their name, the elements aren't rare, but the concentrations found in electronics are low, so grabbing them from discarded electronics is difficult. Of the 12 million kg of rare earths in e-scrap in 2022, around 1% was recycled.

Some bacteria, such as *Vibrio natriegens* and *Shewanella oneidensis*, have penchants for soaking up rare earths from chemical mixtures. Cornell University researchers are genetically engineering the microbes to boost their uptake of rare earths. One strain they recently created adsorbs 210% more dysprosium than the wild type (*ACS Synth. Biol.* 2023, DOI: 10.1021/acssynbio.3c00484).

In the end, though, "bacteria are slow," says Joseph Cotruvo Jr., a chemist at the Pennsylvania State University. His team is going straight for the bacteria's proteins. In 2018, the researchers found that plant-dwelling, methanol-munching bacteria use a type of protein known as lanmodulin to soak up lanthanides, which the bugs need for digesting methanol. The protein has an especially strong affinity for neodymium, the most-used rare earth in electronics. So the researchers, together with Dan Park and colleagues at Lawrence Livermore National Laboratory, anchored the protein on resin microbeads, packed the beads into a column, and used it to grab rare earths out of metal solutions that mimic the composition of e-waste.

Last year, Cotruvo's group found another lanmodulin, which could solve a crucial challenge for rare earth recovery from permanent magnets. The elements' similar sizes and chemistries make separation difficult, and it is typically done using toxic chemicals and large amounts of energy. But the new lanmodulin binds to neodymium more tightly than to the heavier dysprosium. Separating the two elements simply requires a change in pH or the addition of a chelating agent like citrate.

"The protein hangs on to neodymium down to a lower pH value, so you can change the pH to selectively desorb dysprosium and then knock off neodymium at the end," Cotruvo says. "Or add citrate to selectively remove dysprosium because it's less tightly bound to the protein. We are still using chemistry; we're just using biomolecules to help us with that chemistry."

Cotruvo, Park, and their colleagues are hunting for other natural lanmodulin proteins and are engineering known proteins to improve selectivity. They are also on a quest to improve the economics of rare earth recovery by making protein molecules that are smaller and have more rare earth binding sites. A spin-off named ReeTerra, involving Cotruvo as adviser, is further developing the biobased technology for commercialization.

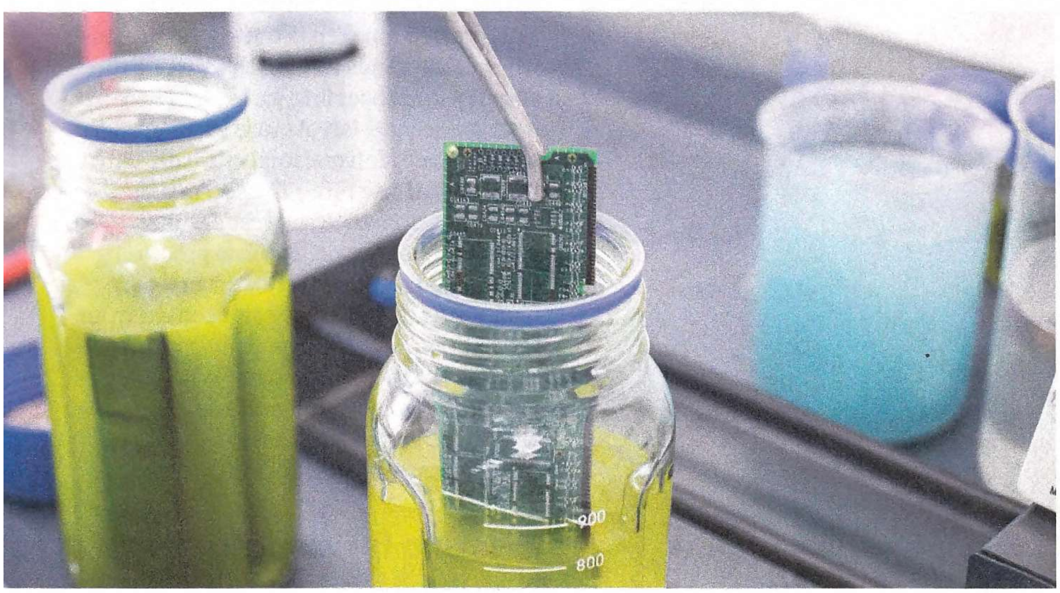
Chasing chemistry

Across the pond, the UK's official coin maker, the Royal Mint, has been around for 1,100 years. The ancient company is now using cutting-edge chemistry from

All that glitters

Electronic waste contains several metals that are valuable or that the US Department of Energy deems essential to economic and national security. Here is the breakdown by weight and value of some of the metals contained in the 62 million t of e-waste generated globally in 2022.

Source: Cornelis P. Baldé et al., *Global E-waste Monitor 2024* (Geneva/Bonn: International Telecommunication Union and United Nations Institute for Training and Research, 2024).



The Royal Mint in the UK is using an undisclosed chemical solution developed by Canadian start-up Excir to dissolve gold from printed circuit boards in minutes.

CREDIT: ROYAL MINT/HUW EVANS AGENCY (LAB); YANG H. KU/C&EN (GRAPHIC) the Canadian start-up Excir to extract gold from PCBs in minutes.

The UK produces the second most e-waste per capita, after Norway. And "a vast majority of end-of-life printed circuit boards leave the UK and go to smelters in Europe or Southeast Asia," says James Cooke, business development director at the Royal Mint's Precious Metals Recovery Plant, 20 min northwest of Cardiff, Wales. "There's a clear gap there in terms of a UK refinery that can deal with the e-waste problem."

At the plant, machines chop up PCBs sent by collection centers around the UK and mechanically sort the material into multiple streams. The precious-metal-rich powder goes to a large reactor filled with a bright green solution—a secret sauce that Cooke says shall remain secret. The solution dissolves gold in just minutes at room temperature and can be reused up to 20 times.

Technicians refine gold from the dark brown precipitate and melt it, forming solid nuggets. The plant sorts the remaining material into various fractions to recover copper, steel, and aluminum and turns plastics and fiberglass composites into building materials. The Royal Mint and Excir have also developed additional chemical processes to extract other precious metals, such as palladium.

Set to operate at full scale by the end of the year, the facility will process 4,000 t of PCBs annually, equivalent to about 40 million laptops, Cooke says. Like Mint Innovation, the Royal Mint hopes to set up small, energy-efficient plants that incentivize more e-waste recycling by making it cheaper and easier than shipping that waste abroad.

Locally based e-waste recycling will also be key to ensure risk-free supply of critical metals, says Jeremy Mehta, a technology manager at the Advanced Materials and Manufacturing Technologies Office of the US Department of Energy (DOE). "We coined the term electric 18 for critical materials that are important to clean energy and are susceptible to supply chain disruptions," he says.

Take rare earths, for example. Today, China produces around 60% of the world's rare earths via mining and refines and processes nearly 90%. At the end of June, the Chinese government introduced rules stating that rare earths belong to the state, sparking worries of a threat to clean energy and high-tech supply chains in countries outside China.

The DOE's $4 million Electronics Scrap Recycling Advancement Prize, launched in March, is the newest in a string of recent initiatives to recover critical materials from e-waste. "Some of these technologies aren't necessarily a replacement for what's already out there, but we want to add value to what's in the waste stream," Mehta says. "Anywhere we can move the needle is important. Aluminum and copper have a higher rate of recovery right now, but we're only getting a small fraction of gallium and rare earths. If we can increase gallium or neodymium recovery or recover all these metals at the same time, that would be ideal."

With DOE funding, materials scientists at the Ames National Laboratory have developed a clever chemical process to recover rare earths from hard drive magnets. Rare earth recovery methods proposed so far dissolve the elements using acids, but the magnetic material first needs to be separated from pulverized e-waste, such as hard disk drives, and then demagnetized and oxidized.

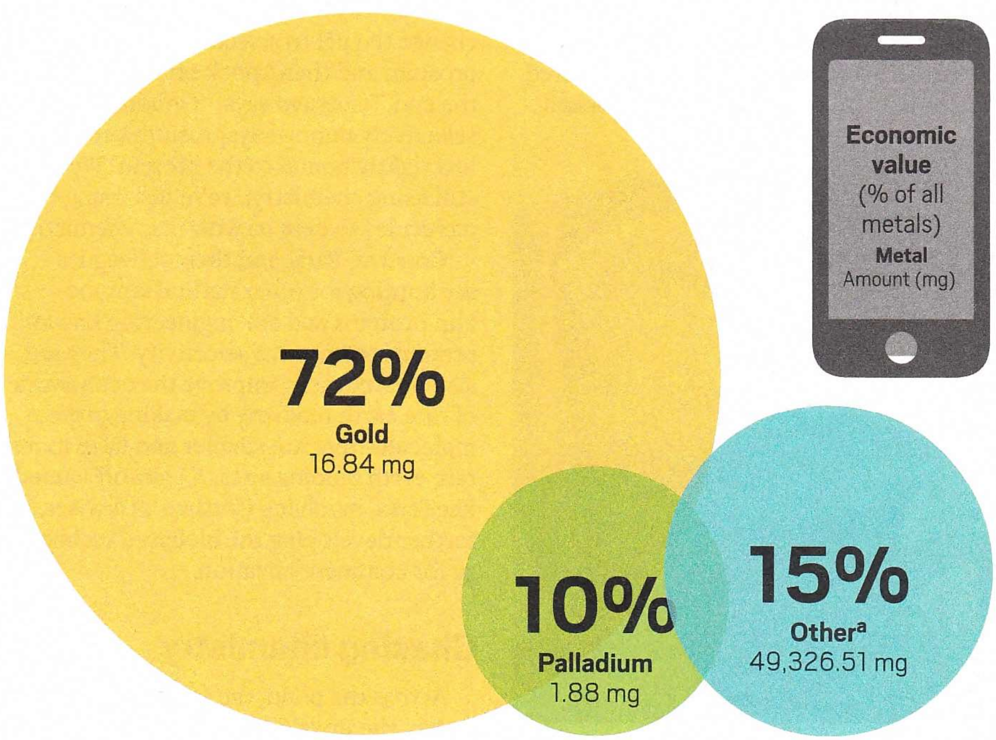
Ikenna Nlebedim and colleagues instead put the entire shredded disk drive in a copper-based solution that selectively dissolves the rare earths, leaving behind other metals for downstream recovery. The basics behind the simple process are taught in high school chemistry, Nlebedim says. "When you put a nail in a copper salt solution, after some time the nail is covered with copper because of ion exchange. Copper from the solution comes out as metallic copper, and iron goes into the solution. Instead of iron, we are using magnets, which are 70% iron and contain rare earths."

The researchers currently use an oxalate-based material to extract the rare earths from the solution. Finally—and this is a key advantage—they are now developing a process to produce rare earths in a form that can be directly converted to metals. Most recycling technologies create rare earth oxides, which are typically converted to metals using harsh hydrofluoric acid. This conversion step is one of the reasons why the US sends rare earths outside the country for processing, he says. "The US is now the second-largest rare earth producer, but we don't have domestic capability to convert those rare earths to metal."

About a 20 min drive west of Ames, Iowa, in the town of Boone, TdVib is processing over 1 t of disk drives per batch in a pilot plant using the technology it licensed from the national lab. The company continues to optimize the technology. "When they licensed it from us, the efficiency of recovery of rare earths from e-waste was 70%. Now they are at 90%," Nlebedim says.

Treasure in hand

Metals make up close to half of an average smartphone's weight (minus the battery). Eleven elements make up 97% of the economic value of the phone's metals. Gold and palladium content is low, but these two elements make up the lion's share of the metal value.



Source: *Resour. Policy* 2020, DOI: 10.1016/j.resourpol.2020.101750.
a Nickel, copper, silicon, magnesium, platinum, neodymium, aluminum, tin, and iron.

Electing for electric

Other companies and researchers are taking an electric approach to tackling e-waste. Australia-based MTM Critical

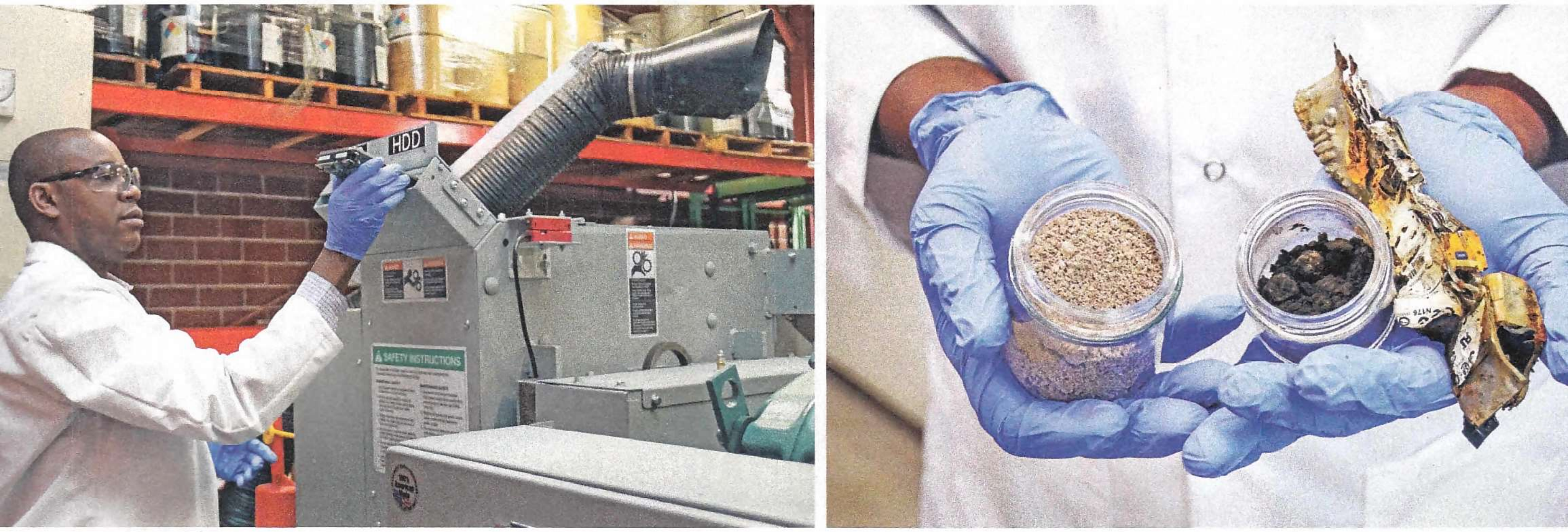
Metals and its US affiliate, Flash Metals USA, are scaling up a technology that extracts metals in a flash. Developed in Rice University chemist James Tour's laboratory, the method, called flash joule heating, involves applying an intense subsecond pulse of electric current to chopped-up e-waste, heating it to more than 2,700 °C. The heat vaporizes the metals, which are condensed or dissolved into low-concentration hydrochloric acid for separation.

Some metals require adding chlorine before flash heating to lower their boiling points, Tour says. The group has used the method to extract 20 types of metals, including gold, from e-waste. "Chlorine is so cheap, and you're getting gold out of it. It's like paying a penny to get a dollar."

MTM Critical Metals claims that the method could be a game changer for extracting rare earth elements. The company flash heats waste material and then applies mild acid leaching. The process reduces acid use and produces less waste than conventional leaching. In tests using coal fly ash, the powdery waste that results from burning coal in a boiler, the company extracted 50% more rare earths—notably, 72% more neodymium—than the conventional method. The company plans to test the process on e-waste.

Tour says the method is efficient because the energy goes into the material instead of an entire furnace. "In smelters, you melt metals together, and then you go through all this wet chemistry. You get acid streams and base streams and flocculation streams. It's an utter mess. And you still have all these tailings with so much metal left behind. You go through 30 steps to get one metal. We can cut the number of steps by a factor of 10."

> "If we can increase gallium or neodymium recovery or recover all these metals at the same time, that would be ideal."
>
> **—Jeremy Mehta,** Technology Manager, Advanced Materials and Manufacturing Technologies Office of the US DOE



Ames National Laboratory materials scientist Ikenna Nlebedim loads a spent hard drive into an industrial shredder (left), the first step of a simple, low-cost, acid-free process to extract rare earth elements (brown powder) from shredded drives. The leftovers (black chunks) are sent on for further metal recovery.

CREDIT: US DEPARTMENT OF ENERGY/AMES NATIONAL LABORATORY

Last resort

Interest in recovering metals from e-waste has soared in recent years, says Morgan Evans, an environmental scientist at Battelle Memorial Institute, an independent R&D organization. Many emerging technologies show promise, but to be successful, they will have to have low environmental impact and be scalable. "Many of these technologies work well on the bench, but put them in a pilot reactor, and they don't perform," she says. A tunable system "that's semiagnostic to what you put into it" would also be vital.

But the single most important metric is cost. "At the end of the day, you have to meet economic markers for things to be adopted by industry," Evans says. "The technology development piece really can make or break some of the economics."

One of the biggest reasons for poor e-waste recycling is a lack of legislation on the collection, management, reuse, and recycling of e-waste, the UN's Baldé says. Even countries with legislation do not always require taking out metals.

"There are collection targets and goals that say 80% of mass has to be recycled," he says. "So all the bulky plastics are recovered for materials or energy. But some of these metals are present in low quantities or low concentrations, so they don't count for much in the overall recycling rate. There's no incentive to boost recycling of critical metals. We need better legislation to, say, push the recovery of X amount of neodymium from hard disk drives."

Regulators also need to pressure companies to design products that last longer, are easier to reuse and recycle, and are cost effective to repair. In fact, many experts agree that recycling should be a last resort. "If a laptop can be reused, it should be," the Royal Mint's Cooke says. "If it can be repaired, let's repair it. If you can salvage the components, let's do that. Our recycling process should only occur at the very end, when nothing else can be done with those circuit boards."

Since 2010, e-waste has grown about five times as fast as collection and recycling, according to the UN report. Tackling the massive problem will take political, industrial, and consumer will. In addition to technologists and policymakers working in sync, consumers also need to be more aware of electronics recycling, Mint Innovation's Barker says. "We're working with local communities to increase education," he says. "It's all moving things in the right direction, but it's going to take an awful lot of momentum and technology to solve this and recycle everything." ■