Recycling renewables

Can we close the loop on old batteries, wind turbines, and solar panels to keep valuable materials out of the trash?

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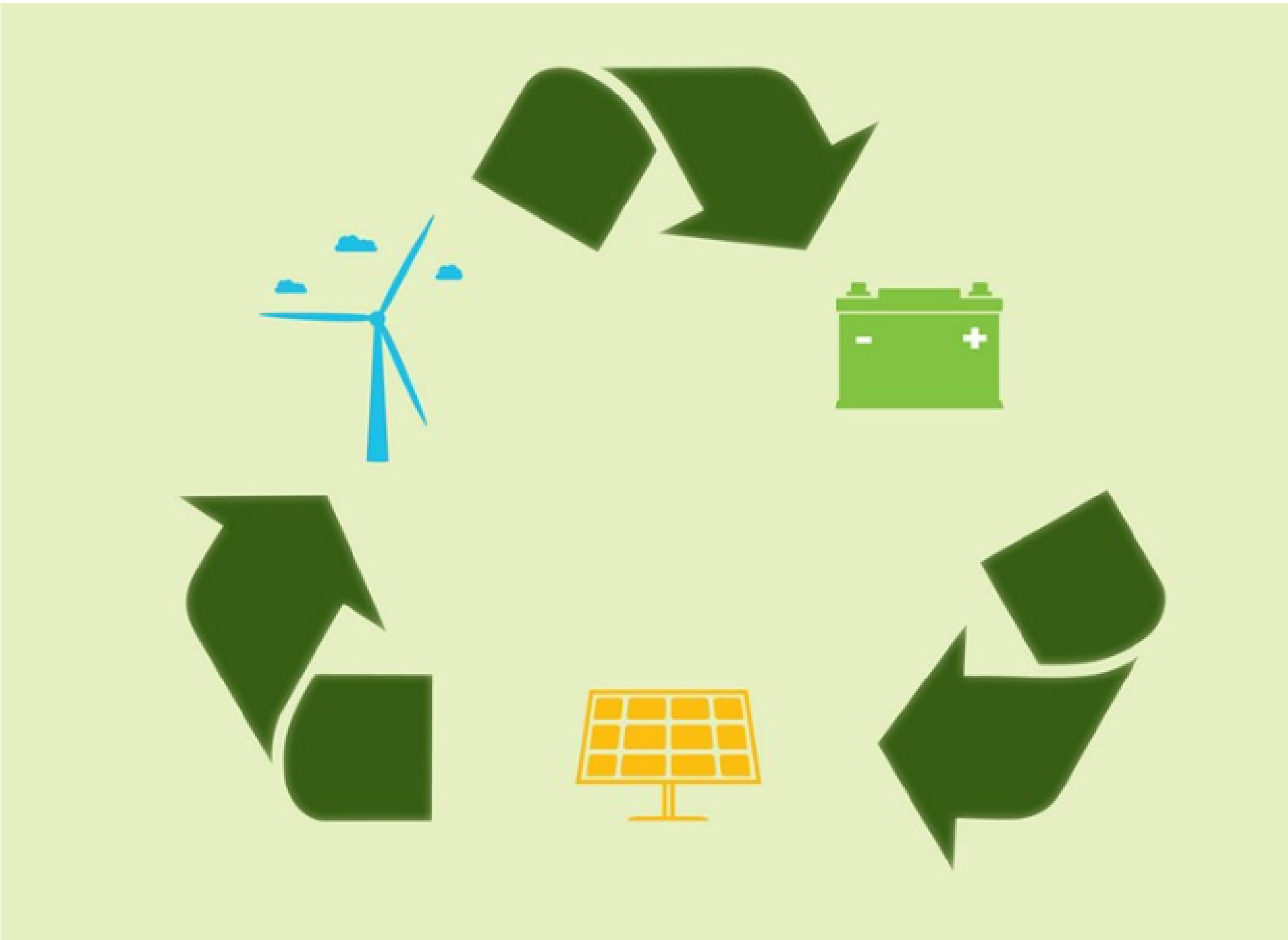


You don't have to be a futurist to imagine a green energy landscape populated by rows of rotating wind turbines, fields of sparkling solar panels, and smooth-running, silent electric cars. Indeed, that utopian vision is almost within reach.

COVER STORY

A renewable energy take-back program

But if the materials that enable those technologies aren't reclaimed, the future's clean energy will be anything but, with views marred by graveyards of old turbine blades, decrepit solar panels, and corroding batteries. Many initiatives are under way to prepare for the arrival of this new type of waste. But in most cases, the solutions are works in progress at best.

IN BRIEF

Renewable energy has been hailed as the great salve for the world's climate change woes. Building massive infrastructure for solar and wind energy, and introducing electric vehicles, will help citizens in developing countries live the lifestyles they desire without the need to burn dirty fossil fuels. But though these technologies have existed for decades, there's no plan to make sure they remain green to the end. Experts forecast hundreds of thousands of tons of old wind turbine blades, batteries, and solar modules will need to be disposed of or recycled in the next decade—and millions of tons by 2050. Read on about the technologies evolving around the world to handle this unusual waste stream.

The potential quantities of waste are enormous. By 2025, waste batteries removed from electric vehicles will total 95 gigawatt hours worth, according to an estimate by Bloomberg New Energy Finance. That pile will weigh roughly 600,000 metric tons.

A similar amount of old solar panels will have accumulated by then, according to projections by the International Renewable Energy Agency. IRENA anticipates solar panel waste could reach 78 million metric tons by 2050. And Europe could see 300,000 metric tons per year of decommissioned wind turbine blades in the next two decades, says the trade association WindEurope.

Thanks to rising demand for renewable energy, manufacturers already face spiking costs and supply constraints for raw materials such as cobalt and lithium. What's more, it takes a lot of human ingenuity and effort to make turbine blade composites, high-purity photovoltaic silicon, and highly structured battery cathodes. Those cleverly engineered materials deserve more than a one-way ticket to trash town.

However, recovering materials from discarded devices remains impractical. They are manufactured to not come apart, even under extreme force or environmental conditions, so they can do their job for as long as possible. And they are made by mixing valuable materials with less valuable ones. Getting the good stuff back out is like unscrambling an egg.

Materials scientists, manufacturers, and waste handlers are working on ways to efficiently reclaim renewable energy materials. But so far, not enough of these devices have reached the end of life to make investing in recycling facilities worthwhile. It's not clear whether a profitable industry will be born in time to prevent clean energy from adding to the planet's already growing pile of waste.

WIND

Wind turbine blades are giant. A single blade for a modern onshore turbine is as long as 60 meters, according to the manufacturer LM Wind Power, and blades are getting longer. Indeed, companies brag about the size of their blades because a bigger sweep generally means more power per tower.

While other wind turbine components, including the tower, gearbox, and generator, are readily recyclable, blades present a challenge. They are typically made from a composite of glass fiber and epoxy or another thermoset resin. The cross-linked polymers cannot be melted down and recycled, in contrast to thermoplastics such as polypropylene.

Credit: National Wind Technology Center
Wind turbine blades, commonly 60 meters long or larger, are difficult to move and to recycle.

And the blades are heavy; a study of turbine blade waste by researchers at the University of Cambridge Institute for Manufacturing estimates that an LM Wind Power blade weighs 15 metric tons. Some manufacturers are making lighter blades by mixing in carbon fiber. In the future, fancier fibers such as carbon nanotubes and high-performance synthetics might lend lightweight strength.

In the U.S. and Europe, wind operators put up the first industrial-sized turbines in the late 1990s. The machines are designed to last 25 years or longer, but some of the blades are being taken down to be replaced by more efficient versions or because they wore out or were struck by lightning.

Even blades from the early generation of wind farms weigh up to 8 metric tons apiece. “This is a big honking blade—you could just throw it in the landfill, but some places won’t accept them,” says Karl Englund, a professor of civil and environmental engineering at Washington State University.

https://www.youtube.com/watch?v=mujVAVfkHNQ&t=26s
Arkema’s recipe for a recyclable wind turbine blade. See how the company made a giant blade from thermoplastic composites.

Englund stresses that a decommissioned turbine blade is a costly nuisance. For wind project operators, transporting even one blade is a logistical nightmare. “There is no use for them. In Sweetwater, Texas, there is a sign on an old blade that says, ‘Welcome to Sweetwater, Texas!’ So that took care of one blade,” Englund jokes.

For the past three years, Englund has been perfecting a blade recycling scheme with the composite firm Global Fiberglass Solutions. The partners have plans to build a recycling center in Sweetwater, which calls itself the wind energy capital of the world.

Recycling starts with trained workers who cut up the blades at a wind farm and stack the pieces on a truck for transport to a centralized facility, Englund explains. There, the pieces are mechanically broken into increasingly smaller bits with a variety of machines until they reach a size that contains fibers of a desired length for the material's next life.

The material can then be combined with adhesives and pressed into high-performance composite panels similar to wood-based particleboard or oriented strand board. The glass fibers give the panels fire and moisture resistance, Englund says, making them ideal for commercial and industrial buildings. "We have quite a few people who want this panel after seeing it."

Others have attempted to process old blades and reclaim glass or carbon fibers. In 2002, Danish wind technology engineer Erik Grove-Nielsen founded a recycling firm called ReFiber. He developed a pyrolysis technology for turning glass fiber in old polyester or epoxy wind turbine blades into a fibrous material suitable for use as building insulation. The anaerobic process involved heating turbine pieces to 500 °C in a 6-meter-long rotating gas oven.

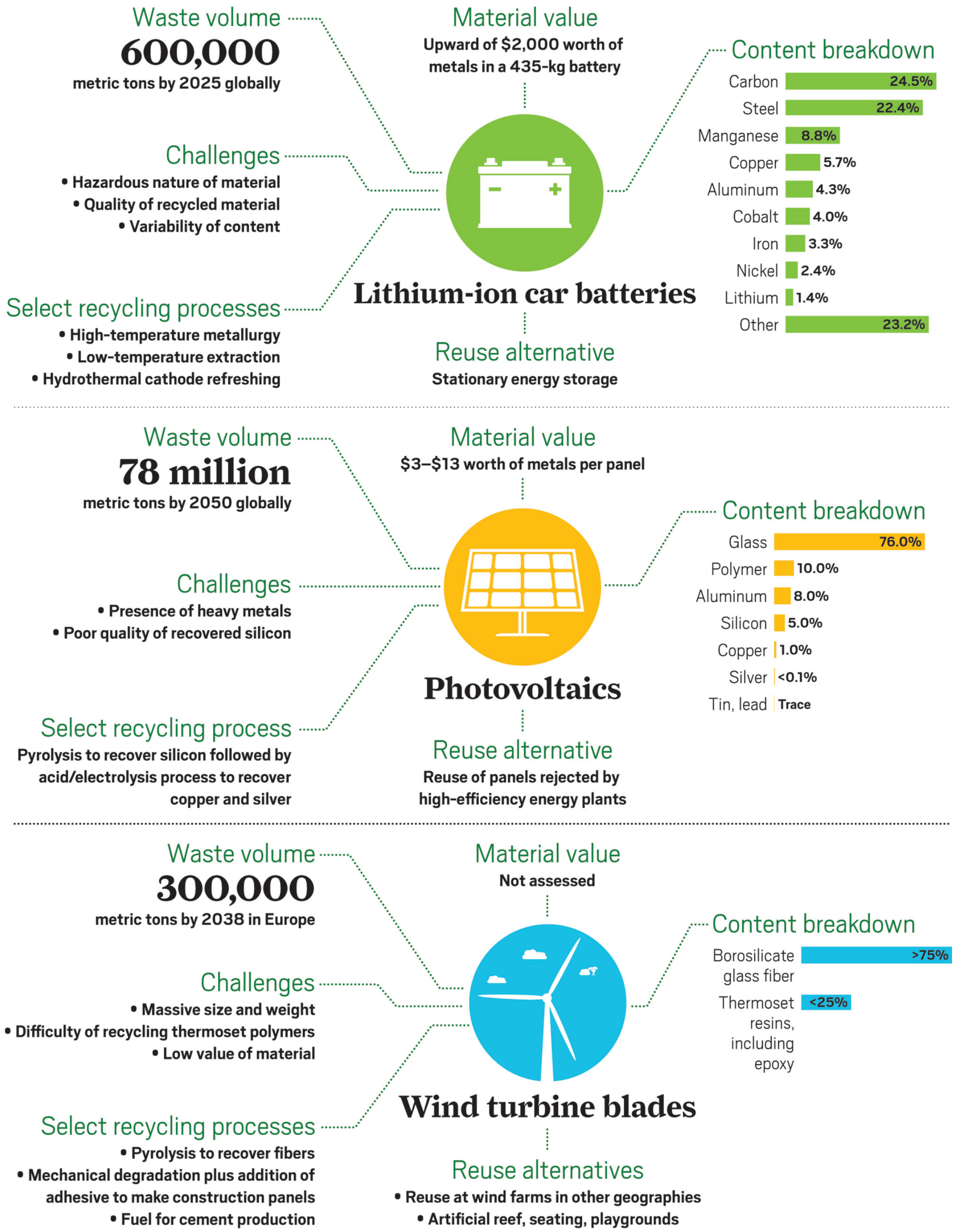
ReFiber had planned to raise capital and build a 5,000-metric-ton-per-year facility. But without a consistent supply of old blades, the firm ceased operations in 2007, says Grove-Nielsen, who now works as a consultant for the wind farm builder Siemens Gamesa Renewable Energy.

But processes that use pyrolysis or other high-heat methods generally yield weaker fibers that can't be reused in high-value composites. "You can end up just making really expensive garbage," Englund contends.

The French specialty chemical firm Arkema says thermoplastic resins are the way to go to make blades recyclable. To prove it can be done, the company made a single blade last year using a composite of glass fiber and methacrylate resin. Unlike epoxy, the resin can be melted and recycled. It's not clear whether blade manufacturers will make the switch.

In Europe, wind turbines may find a second life in countries just starting to adopt wind energy, thereby delaying the end-of-life problem. "A good example is the very first Danish Bonus—now Siemens—turbine, taken down after 33 years of successful operation," Grove-Nielsen says. "The same turbine is now operating in southern Italy near Bari."

Other uses for old turbine blades take advantage of creative thinking. Independent wind turbine engineer Behzad Rahnama wrote a graduate school thesis on repurposing offshore wind turbines into artificial reefs. Although the idea hasn't been tested, it has drawn a lot of interest, Rahnama says. He points out that any materials used in the blades would have to be nontoxic to marine life.



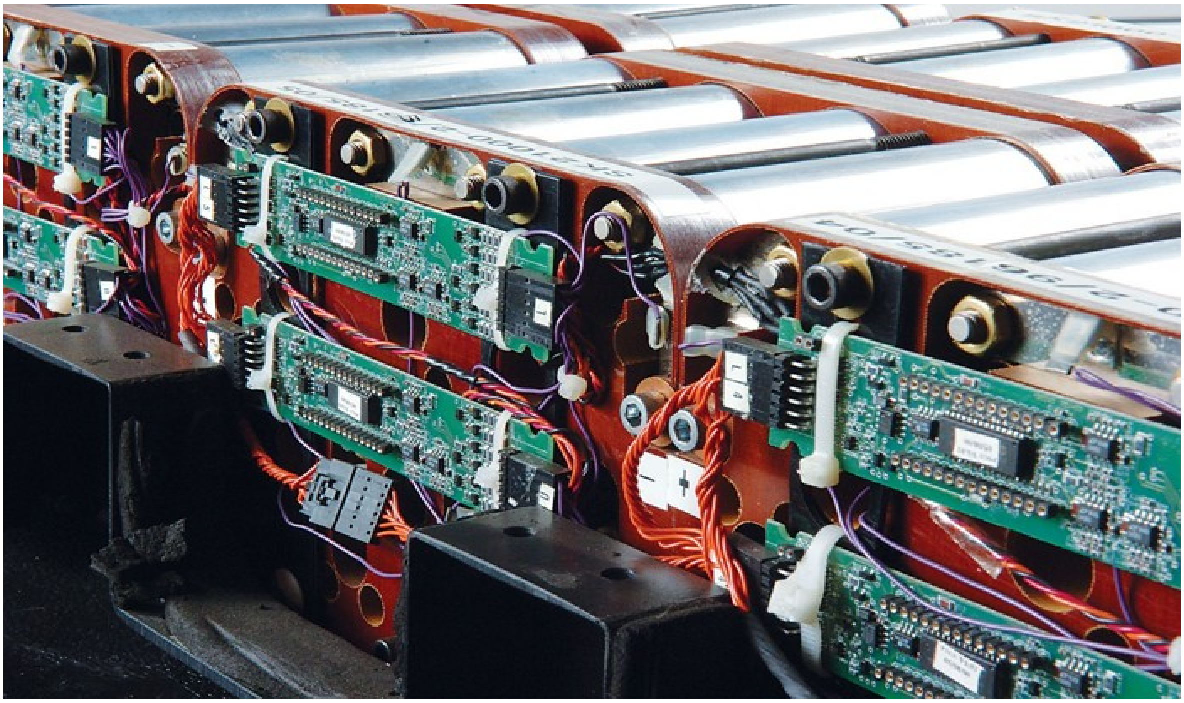
Mining the waste

Renewable energy technologies contain valuable materials; the trick is to reclaim them economically. Sources: Bloomberg New Energy Finance; Esticast Research & Consulting; FRELP; Gabrielle Gaustad, Rochester Institute of Technology; InfoMine; International Renewable Energy Agency; London Metals Exchange; ReFiber; Resour. Conserv. Recycl., 2014. DOI: 10.1016/j.resconrec.2013.11.008; WindEurope

BATTERIES

Each year, approximately 300,000 metric tons of lithium-ion battery waste is generated around the world, says Sheetanshu Upadhyay, an analyst with India's Esticast Research & Consulting. Most of those batteries come from mobile devices, but that waste will soon be overshadowed by old electric car batteries. Sales of plug-in electric vehicles are expected to surpass 2.6 million in 2020, according to Navigant Research.

Car batteries reach the end of their lives when they can be charged to only 80% of their capacity, according to Matt Keyser, who leads the U.S. National Renewable Energy Laboratory's battery R&D efforts. NREL estimates their useful lives to be about 15 years. After that, they can be reused in stationary storage applications or recycled.



Recycling electric vehicle batteries requires disassembling large packs like this one, then retrieving valuable metals from individual battery cells.

Keyser says NREL's tests show that used car batteries are good for storing power for the electrical grid, a less-demanding application. But, he adds, "There are lots of different manufacturers, battery chemistries, management and communication systems, and sizes and shapes of batteries." Keyser knows of no system that can assess different used batteries or integrate them to operate together.

Using a single type of battery may work better. Nissan has been evaluating the use of old Leaf electric car batteries in stationary storage systems. A pilot study showed it to be a practical approach, Makoto Dave Yoshida, general manager of Nissan Motor in the U.K., told delegates at a recent workshop on battery recycling in Paris.

With the world's largest fleet of electric vehicles on the road, China is also the world's largest ticking time bomb when it comes to end-of-life lithium-ion batteries. It's not a pressing problem now because the cars entered service in just the past three years, notes Wijaya Ng, head of the China practice at Ipsos Business Consulting, a management consulting firm.

But officials in Beijing see the future pile of waste batteries as a problem that needs to be addressed now. In February, the Chinese government issued regulations requiring electric vehicle manufacturers to build an infrastructure to recover used batteries by Aug. 1. Even though it’s not clear how they will be dealt with, “dealers must be ready to handle those batteries,” Ng says.

“You could say that the infrastructure will only be symbolically in place in August, but the responsibilities of the stakeholders have been clarified,” Ng explains. He expects car and battery makers to invest in recycling only reluctantly, because making batteries from new materials is currently cheaper than using recovered ones.

Still, carmakers are doing a good job of showing enthusiasm for recycling. BYD, one of China’s leading electric vehicle makers, plans to open a car battery recycling facility this spring in Shanghai, company spokesperson Mia Gu says. Operational details have not yet been disclosed.

In Europe, a 2008 regulation known as the Battery Directive requires governments to promote battery recycling. A German law stipulating that old batteries must be recycled underpins recycling growth in Europe, Upadhyay says.

Lithium-ion battery packs for electric cars are made of tens to thousands of individual cylindrical or rectangular battery cells in a large plastic case that also holds various sensors and circuits. The most valuable substances inside the cells are active materials that make up the cathode and anode; the majority of a cell’s mass comes from structural components made from steel, carbon, and aluminum.

The active materials of most interest to battery recyclers are the transition metals cobalt and nickel, found in the cathode. Different lithium-ion batteries contain various ratios of those metals, as well as lithium and in some cases manganese or iron.

In addition to regulatory mandates, the European Commission says high prices for cobalt are a driver for recyclers, although only 16% of cobalt in batteries is reclaimed today. Lithium and the anode materials graphite and silicon cannot be economically reclaimed.

Belgium-based Umicore is both a major producer of battery materials and Europe’s largest lithium-ion battery recycler. It uses a high-temperature technology in its facility near Antwerp, Belgium. There, it can recycle up to 7,000 metric tons per year of all types of lithium-ion batteries, equivalent to what’s inside 35,000 electric vehicles.

Umicore’s process converts the batteries into two fractions. An alloy fraction containing cobalt, nickel, and copper undergoes further separation. A slag fraction can be added to concrete.

The batteries can be fed directly into the reactor, which avoids the need for potentially hazardous pretreatment, Umicore says. The company cleans the resulting gases of dioxins and volatile organic compounds. Energy consumption is minimized by using energy still present in the batteries. “Depending on the exact battery mix, only little or no external energy has to be added to the process,” Umicore says.

Umicore has agreements with a number of automakers, including Nissan, Toyota, and Tesla, to recycle old lithium-ion batteries from their vehicles. It then sells the resulting alloys back to battery producers and car companies.

In the U.S., lithium-ion batteries are not considered hazardous waste and can be discarded in the normal municipal waste system. But some firms have developed know-how in reclaiming materials from battery waste.

One of them is Retriev Technologies, which operates large-scale facilities in Ohio and British Columbia. The company says it has recycled lithium batteries of all types for over 20 years.

Large battery packs from vehicles are first manually disassembled. The separated cells are then fed into a crusher, which smashes them in a liquid that prevents emissions and chemical reactions. Crushing the cells results in two streams: metal solids with varying amounts of copper, aluminum, and cobalt; and metal-enriched liquids that are dried and then purified off-site.

But metals like cobalt must be made very pure to be used again in batteries, NREL's Keyser says. Extracting high-purity metals from streams of mixed metals is very expensive. Industry watchers agree that high-temperature recycling methods like Umicore's produce metals that are not cost competitive with newly mined metals and that the economics of battery recycling require a fee to be paid by the generator of the waste. Umicore declined to respond to C&EN's questions about the market value of the reclaimed metals or the cost of extracting them.

In addition, making new cathodes from recycled materials is a costly process. According to Zheng Chen, a professor of nanoengineering at the University of California, San Diego, it should be possible to extract spent cathode material from lithium-ion batteries and refresh it for reuse without going back to the original metal constituents.

Chen says his group started with lithium cobalt oxide batteries because of their relatively simple chemistry. His goal was to end up with cathode material with a crystal structure and ratio of lithium and cobalt that matches brand-new cathodes. To do that he turned to the same hydrothermal reaction used by cathode manufacturers.

Used cathodes are depleted of lithium to varying degrees. The hydrothermal process allowed Chen to replace the missing lithium without first analyzing the cells. With the stoichiometry correct, the next step is thermal annealing to create microstructures to maximize the recycled material's electrochemical performance. Similar strategies should also work on other flavors of lithium-ion battery cathodes, he suggests.

U.S. R&D firm OnTo Technology has already patented a hydrothermal process to reclaim functional cathode materials. President Steve Sloop says OnTo is working with nickel-containing cathodes that are common in electric vehicle batteries.

Sloop claims that the process generates high-value cathode materials at a low cost. "We can crack those batteries open, get those cathodes out, and sell them back to the battery firm. That makes an old battery an asset rather than a liability." But even a great chemical process is not enough to solve the battery waste dilemma. "You have to get to the scale that can handle a ton of batteries per day—and that would be a substantial capital expenditure," Sloop points out. The facilities' cost, he suggests, would be similar to that for making aluminum from bauxite ore—hundreds of millions of dollars for a large-scale operation.

Additionally, old batteries can be hazardous to transport. In the future, Sloop suggests, electric vehicle manufacturers or battery firms may opt to set up regional networks to take back and recycle waste batteries.

To handle the batteries at the facility, Chen and Sloop agree that automated machinery is needed to break open the battery cells to obtain the cathode materials. “In the lab I can have the students spend two hours opening the batteries, but I don’t have 25 million students,” Chen says.

SOLAR

The question of what to do with old solar panels is likely to be solved first in Europe. Not only does Europe have about 70% of global installed photovoltaic (PV) capacity, but the European Union is also the only region in the world with a regulation—known as the WEEE Directive—that has banned electronic products, including PV panels, from being landfilled.

The EU estimates that the region currently generates 30,000 metric tons per year of waste PV panels and that this will rise to about 500,000 metric tons per year in the next two decades. PV Cycle, a European PV recycling industry association, estimates that its members have collected 17,000 metric tons of PV panels since 2010.

Credit: PV Cycle

These old solar panels will be recycled; however, not all the valuable materials can be reused.

“Strict regulation means that we are a step forward regarding the end-of-life management of PV,” says Bertrand Lempkowicz, marketing manager for PV Cycle. “In Europe, the WEEE legislation will definitely help.” In Asia, where solar panel waste is already accumulating, they are just starting to think about what to do, he says.

Most solar panels contain a layer of crystalline silicon semiconductor sandwiched between glass sheets and tough polymer films, all in a frame made of aluminum. The surface of the semiconductor is embedded with trace amounts of silver used as a conducting material, as well as lead and tin solder.

Problems associated with improper disposal of waste PV panels can include leaching of heavy metals such as lead, according to a European Commission study.

In a bid to avoid such environmental issues and to maximize material recovery, the EU has funded research including the Full Recovery End of Life Photovoltaic (FRELP) project. Italian mining technology firm Sasil, one of the project’s members, has been running a pilot facility based on technology developed by FRELP. Opened in 2015, the facility can take in 3,500 metric tons of PV panels annually. Other project members include the Italian glass technology institute Stazione Sperimentale del Vetro.

The FRELP process recovers silicon and other metals by heating the panels in a furnace; an acid dissolving step and filtration then recover silicon. Other metals are recovered via electrolysis. Sasil says it is able to recover 93% of materials from used PV panels. Most of the remaining material is plastic, which is burned in the furnace to provide additional energy.

While the FRELP process marks a new European standard in PV panel recycling, it is not problem-free: For every 1,000 kg of PV panel waste, about 20 kg of metals, including tin, aluminum, lead, and zinc, are recovered as hydroxides and landfilled. A further 2 kg of material is likely lost as nitrous oxide emissions during electrolysis, and 5 kg of ash results from the reduction of fluorine at the furnace phase.

The quality of the silicon recovered is not high enough for reuse as a photovoltaic material but is suitable to be used in specialty aluminum and steel alloys, Sasil project manager Lodovico Ramon says.

Meng Tao, an engineering professor at Arizona State University, says an electrochemical process his team is developing can extract purer metals from solar cells. The metals would be worth $13 per module, he says, enough to pay for the recycling, compared with about $3.00 in the PV Cycle process.

Tao's process, called sequential electrowinning, is like electroplating in reverse. After the glass is removed from a panel, the interconnected solar cells are immersed in a heated nitric acid solution to dissolve silver, tin, copper, and lead. The leached solution is cooled, causing tin dioxide to precipitate. When different voltages are applied, the other metals come out of solution and are deposited on a series of electrodes.

A secondary process soaks the remaining silicon first in hydrofluoric acid and then in sodium hydroxide. That etches off the remainder of the nonsilicon materials, such as electrodes, and leaves behind a high proportion of solar-grade silicon.

Making recycling profitable would help close the loop on solar in the U.S. Unlike in Europe, one can just toss an old solar panel in the local dump—though that could change. "We have a landfill crisis. We're just running out of space," says Dustin Mulvaney, professor of environmental studies at San Jose State University.

"Communities and counties that have waste management challenges are going bananas with the idea that they have to maybe landfill these things. They don't decompose or even stack well," Mulvaney says.

Some U.S. recyclers do take in solar modules for processing. Generally, each panel is disassembled and the aluminum and glass are recycled. But, as is the case with other types of electronic waste, the semiconductor material is generally not.

The solar industry is ready for an upgrade. “We would like to nurture and develop processes unique to photovoltaics so we can reclaim more of the valuable materials,” says Evelyn Butler, senior director of codes and standards for the Solar Energy Industry Association, a U.S. trade group.

The most valuable solar material component is silver, Butler says, but newer modules contain less of the precious metal. “We have to convince our partners in recycling that they have a future, even though our industry has been working hard to bring down the cost curve for materials,” she says.

It will likely be decades before the modules deployed in the largest utility installations reach the end of their lives, but figuring out the timeline is difficult, Butler points out. “Is it 20 years, 25, or even 35 years? Often the large-scale projects are in the harshest environments—in the desert, where there is no shade and big temperature changes.” Some panels could be reused elsewhere once their performance dips below that required by utilities.

For now, solar waste is mainly generated when modules break or fail to match their warranties, in which case the manufacturer is on the hook for disposal or recycling. After the warranty expires, panels are the responsibility of their owner.

Indeed, it is common that manufacturers of renewable energy technologies do not consider themselves accountable for recycling their products. “The amazing thing is that the producers don’t see the business opportunity,” says circular economy proponent Michael Braungart, academic chair of Cradle to Cradle for Innovation & Quality at Erasmus University. “It’s like making a plane that is not designed to land—it’s ridiculous.”

Industry experts and watchdogs agree that if old solar panels, wind turbine blades, and electric car batteries pile up for lack of good recycling options, waste will become a black eye for these supposedly clean industries.

With reporting by Jean-Francois Tremblay.