To make electric vehicles environmentally and economically sustainable, the industry will need to take a fresh look at how lithium-ion battery packs are made and recycled.

How green is your electric vehicle?

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The market for electric vehicles (EVs) is revving up. More than 773,000 electric vehicles were sold last year, nearly half of them in China alone. Forty-one million EVs could be on the roads worldwide by 2040, according to a new report by Bloomberg New Energy Finance (NEF). They would displace 13 million barrels of crude oil per day.

But nothing comes free. Depending on the electricity source that is used to charge it, an EV can still produce global warming pollutants, albeit far fewer than an equivalent gas-gulping car, according to the Union of Concerned Scientists. And manufacturing an EV actually results in higher emissions, mainly because of the giant battery that powers it. Every stage of a battery's life cycle requires energy and produces waste. Falling EV battery prices—they hover around \$200/kWh today—do not include these hidden costs.

By the middle of the next decade, more than 95 GWh worth of used batteries will be extracted from hybrid and electric vehicles, according to Bloomberg New Energy Finance. Many could get a second life storing wind and solar energy on the grid. But once they cannot hold enough charge even for that, most may end up in the landfill. By some estimates, less than five percent of lithium-ion (Li-ion) batteries are recycled today because of a lack of incentives and recycling infrastructure.

In the quest for faster, longer-range vehicles, manufacturers have focused on battery performance. But for EVs to be truly green, Li-ion batteries that power them need a circular economy modeled after that of lead-acid batteries, more than 90% of which are recycled. That means not only concerted efforts on recycling, but also developing new material chemistries and manufacturing processes with reuse in mind.

"If we're introducing electrified vehicles with the objective of reducing greenhouse gas generation then we don't want to introduce new concerns and shift the problem," said Renata Arsenault, an energy-storage and materials researcher at Ford.

A circular economy balances economic development with resource protection. The goal is to keep valuable or harmful materials out of landfills, efficiently use and recover useful elements, and ideally reuse all of a battery's components. This makes environmental and fiscal sense.

Li batteries contain cathodes made of lithium metal oxides or phosphates, in which the metal can be various combinations of cobalt, nickel, manganese, and iron. Anodes are typically made of graphite. Mining for these materials is concentrated in certain geographical regions—75% of Li comes from Argentina, Bolivia, and Chile, 65% of cobalt comes from the Congo region, 65% of graphite from China, and much of the world's nickel is in the Philippines and Russia. Mines can have poor environmental and labor practices. In addition, there might not be enough material left to mine to meet soaring electronics and EV demand. Supplies of cobalt and nickel are most fragile, leading to relatively high prices.

Manufacturing lithium-ion batteries requires a tremendous amount of electricity. Swapping virgin material with recycled materials to make batteries would reduce this electricity use. Even though the standard pyrometallurgical recycling process, which involves melting batteries, requires energy, "metallurgical recycling is still less energy-intensive than virgin material production," said Linda Gaines, a transportation systems analyst at Argonne National Laboratory.

This would mean fewer emissions, especially of carbon dioxide and sulfur dioxide, said Gaines. For lithium manganese oxide cathodes, for instance, her analysis shows that recycled materials (cathode, aluminum, and copper) could halve energy use.

And since raw materials are half the cost of a battery, according to Argonne's Battery Performance and Cost Model, reusing battery materials would also help ensure a lasting material supply and stable prices. That means sustainable, low-cost EV batteries in the long term.

One of the biggest hurdles to a commercial-scale closed-loop system is quantity. EVs are a nascent market, and there aren't enough batteries reaching end-of-life, said Gaines. Battery recyclers today have relatively small input streams, and it is hard to test new recycling technologies at scale. Major Chinese recycler Guangdong Brunp Recycling Technology says that their biggest challenge is collecting enough EV batteries. Currently, 98% of the batteries the company processes come from consumer electronics.

Another big hurdle for Li EV battery recycling to become mainstream is that the recovered materials will need to perform as well as virgin materials for a comparable cost. In the case of lead-acid batteries, a recycler sells recycled materials for more than the price they paid for a scrap battery. So the cost of recycling is embedded in the battery's retail price. That is not the case for Li batteries, and considerable research is required before they can achieve a closed-loop profile comparable with lead acid. "There needs to be rigorous quality control on recycled material," said Gaines. "Maybe some kind of standard, say a purity requirement or guaranteed number of cycles."

The challenge with recycling Li batteries is that unlike lead-acid or nickel metal-hydride batteries, they don't have a standard

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https://doi.org/10.1557/mrs.2017.122 Published online by Cambridge University Press

chemistry. Energy-intensive pyrometallurgical recycling yields individual elements, which works for high-value cobalt. But cathodes in most EV batteries today are composed largely of nickel and manganese, which are less valuable than cobalt. "There's a need for recycling technology that can economically process nickel and manganese," said Michael Slater of San Francisco-based battery maker Farasis Energy.

Car batteries are also designed to last for a long time and won't return for recycling for maybe 10–15 years after their second life. "There's conflict between design to recycle and design to last," said Gaines. "Even if you can recover active material and it's got great quality, is it a dinosaur? You don't know what's going to be the best battery technology in 15 years."

Brunp, which plans to open a new facility that can process 100,000 tons of material, uses hydrometallurgical recycling, an energy-efficient process that recovers high-purity metals. Batteries are ground, physically separated, and then immersed in aqueous solutions to leach Ni, Mn, and Co. The process recovers more than 98% of NMC cathode material, which can be reused in batteries.

Promising new recycling technologies are in the pipeline. Farasis and startup OnTo Technologies in Bend, Ore., are developing direct recycling processes that recover the entire active cathode material instead of individual elements. The process involves physically crushing battery electrodes, separating materials using sieves or magnets, and then purifying them. With minimal processing and the addition of more lithium, the active materials are ready for new batteries. And the best part is that direct recycling works with most Li metal oxides. "Some require tweaking of the processing technology, but it's been very flexible to various materials," said Steve Sloop, CEO and the mind behind OnTo's process.

X-ray diffraction and other material analysis techniques show that virgin and recovered materials are essentially the same. And new battery cells made with refurbished cathode materials have nearly the same energy-storage capacity. Slater said that more engineering of the surface chemistry should eliminate the difference in the materials. "There have been different levels of success at lab scale, but we haven't scaled the process up," he said.

Meanwhile, after nearly a decade of finessing his process, Sloop said Nissan now plans to buy OnTo's upcycled battery materials.

That's a great first step toward closing the loop between manufacturing and recycling. How could this become the norm? The answer is uncertain. But if recent workshops and conferences are an indication, the issue is on the minds of public and private players. "Ensuring that batteries are recycled or looking at the most sustainably beneficial solutions for end-of-life batteries is very much front and center," said Arsenault.

Slater believes that battery makers are best situated to develop the technology for recycling because "we know in detail what's inside." Plus, it can be the most financially efficient thing to do. The same technology that recycles end-of-life batteries can also be implemented at the manufacturing plant to reprocess quality-control rejects and scrap material generated during manufacturing, he said.

It's critical to think about the battery's end of life during its design and development. Standardizing battery sizes and chemistries would help, as would engineering battery outer layers that are easier to deconstruct to get to the valuable materials inside, and designing cathode compounds that are easier to desynthesize. "There are lots of opportunities for imaginative development to accomplish both goals: make something that works but can also be recycled," said Gaines.

Another option is to use materials that are easier to reclaim, said Timothy Ellis, president of RSR Technologies, a private R&D company based in Dallas, Texas. Like going back to cobalt-based cathodes precisely because they are expensive and have recycling value "which might accelerate collection," he said. "We may have to give up some life cycle or max performance, but maybe we're better off improving the performance of materials that are better and easier to recycle."

Alternative chemistries could also be key. Ellis pointed out that battery developers need new electrolytes anyway to help them reach voltages over 4.7 V. This is a perfect chance for materials scientists to invent new cathode materials and electrolytes that perform well and take less energy to produce.

Policies that mandate responsibility for end-of-life disposition of batteries are helping in China and Europe, although exactly how much is anyone's guess. The EU Battery Directive requires at least 50% of batteries by weight to be recycled. This has increased recycling rates, but they still might not meet the 45% recycling target. No such mandate exists in the United States.

As EV sales ramp up, batteries are expected to start entering the recycling stream with high volume by 2020. But there's no time to wait. Comparing various recycling processes to different chemistries and designs should be carried out even as the eventual design and material composition of those batteries remain unknown. Ultimately, the public would benefit from a true battery cost calculation that compares battery chemistries not only on the basis of the cost of manufacturing, but the full life-cycle cost, including recycling.

A sustainable, closed-loop battery-manufacturing ecosystem will benefit battery and vehicle manufacturers, recyclers, consumers, and the environment. "We can't make holes in the Congo and bury batteries made with those materials in landfills in New York," said Ellis. "We need better science to find a solution." □

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