**Maryland Department of the Environment**
**Report on Lithium Ion Battery Recycling**
**December 1, 2019**

## Introduction

The 2019 Joint Chairmen's Report requires the Maryland Department of the Environment (MDE) to submit a report outlining how MDE will establish and fund a lithium ion battery (LIB) recycling program. The report is to contain information on how LIB recycling may be incorporated into the Maryland Recycling Act (MRA) and the steps needed to create a statewide program to recycle lithium ion batteries.

## Background

LIBs are commonly used for medical equipment, power tools, electric vehicles (EV), and portable electronics such as laptops, cameras, mobile phones, video cameras, and watches. Additionally, household type (e.g., AA, AAA, etc.) LIBs are beginning to make their way onto the market. The use of LIBs is growing, driven largely by LIBs' advantages in EV applications. LIBs have among the highest energy densities of current battery technologies, meaning that relatively small and light batteries can store and provide a large amount of energy. They are also lower maintenance than other types of batteries. The U.S. Department of Energy (USDOE) notes that "the growth in [electric vehicle] sales, as well as increased demand for consumer and stationary uses, are expected to double the demand for lithium-ion batteries by 2025 and quadruple the demand by 2030."[1]

As production and use of LIBs increase, the demand for certain scarce inputs to LIBs, particularly cobalt, nickel, and lithium, increase as well. According to USDOE, the production of virgin cobalt is highly centralized, with 58% of the world's supply coming from the Democratic Republic of Congo, and 80% of that supply going to China for refining.

The need for inputs for the production of new LIBs represents an opportunity for LIB recycling as higher prices for reclaimed metals improve the economics of the recycling process. Recycling of LIBs, both in the U.S. and abroad, has been relatively low in recent years (an estimated 3 to 5%). However, because of the significant growth in the market, many recycling experts project sharp increases in LIB recycling in coming years.[2] In fact, according to a recent analysis by Creation Inn, a consultancy specialized in energy storage and the circular economy, the total amount of global recycled lithium could reach 5,800 metric tons (30,000 metric tons of Lithium Carbonate Equivalent[3] (LCE)) by 2025. More than 66% of the LIBs, or 191,000 metric tons, are expected to be recycled in China and 76% of the cobalt in 2025 is expected to be recycled in

[1] U.S. Department of Energy, Vehicle Technologies Office's Research Plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries (2019). This plan is included as Attachment 1.

[2] Pagliaro, Mario and Francesco Meneguzzo, Heliyon, "Lithium battery reusing and recycling: A circular economy insight" June 15, 2019. This document is included as Attachment 2.

[3] Kay, Amanda, Investing News, "What is Lithium Carbonate?" August 15, 2018– lithium carbonate is often "the first chemical in the lithium production chain," with compounds like lithium hydroxide (used in batteries) being produced with subsequent steps if needed. Looking beyond batteries, lithium carbonate is used in ceramics, glass, cement and aluminum processing. This document is included as Attachment 3.

China without taking production scrap or other sources into account.[4] While minerals from recycled batteries, including lithium, cobalt, nickel, and manganese, can be found in new batteries already, the volumes are low and insufficient to keep up with the growing demand for new LIB batteries. This is expected to change rapidly; for example, by 2025 the amount of cobalt from recycled batteries is expected to reach almost 20% of the demand.[5]

In addition to providing recovered metals to support the growing EV market, and reducing the energy and water needed to produce virgin inputs, LIB recycling is important for other environmental reasons. Globally, an estimated 11 million metric tons of LIBs are expected to reach end of life between now and 2030.[6] Without proper recycling channels, those LIBs can make their way to disposal and recycling facilities that are not designed to safely manage LIBs. Specifically, LIBs pose a fire and explosion risk when handled at typical solid waste and recycling facilities. When crushed, punctured, ripped, or dropped, the separation between the cathode and anode electrodes in the battery becomes damaged, and the battery can discharge or short circuit. This effect can lead to fires and explosions at recycling and solid waste facilities as consumers unknowingly place LIBs in trash cans or single stream recycling. A survey in California found that 83% of solid waste facilities had a fire with 65% of those reported fires due to LIBs.[7]

In order to ensure the availability of important inputs to LIBs in the United States, USDOE published a July 2019 Research Plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries.[8] The plan includes three initiatives:

1. Supporting early-stage research into low- and no-cobalt LIBs;
2. Establishing a LIB recycling research and development center, called ReCell, to develop innovative and efficient recycling technologies; and
3. Launching a LIB recycling prize, which invites entrepreneurs to create innovative solutions to current challenges associated with collecting, storing, and transporting LIBs for recycling.

**<u>Existing LIB Recycling Opportunities in Maryland</u>**

In order to determine the steps needed to create a statewide LIB recycling program, MDE researched current LIB recycling opportunities for Maryland residents and businesses. LIBs included in electronic devices may be recycled when old electronics are recycled. In Maryland, electronics recycling is offered through a combination of private and local government programs. Under Maryland's electronics recycling law, manufacturers of covered electronic devices[9] must

---

[4] Messenger, Ben, Waste Management News, "Recycling Could Supply 9% of Global Lithium Demand by 2025" December 4, 2017. This document is included as Attachment 4.

[5] Circular Energy Storage, Press release: Recycled lithium to reach 9%of total lithium battery supply in 2025, November 30, 2017. This document is included as Attachment 5.

[6] Jacoby, Mitch, Chemical and Engineering News, "It's time to get serious about recycling lithium-ion batteries" July 14, 2019. This document is included as Attachment 6.

[7] Call2Recycle, Avoid the Spark Campaign Continues Battery Safety Awareness in the Bay Area, October 4, 2018. This document is included as Attachment 7.

[8] U.S. Department of Energy, Vehicle Technologies Office's Research Plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries (2019).

[9] Covered electronic device means a computer or video display device with a screen greater than 4 inches measured diagonally.

register annually with MDE and pay a required registration fee. The fee is reduced for manufacturers that offer approved electronic device takeback programs. Takeback programs allow consumers to return their end-of-life electronic devices to be recycled at no cost to the consumer, either through a mail-back program or at designated collection locations. Manufacturers with approved takeback programs can be found on MDE's website at www.mde.maryland.gov/ecycling.

Most local governments in Maryland collect electronics for recycling. Currently 22 out of 24 jurisdictions offer "ecycling" programs. County ecycling programs are designed to accept electronics from residents (not businesses) of the county and typically include desktop computers, laptop computers, and certain video displays.

Some counties also collect batteries through household hazardous waste (HHW) collection programs. MDE surveyed counties on local programs for the collection of LIBs. Eighteen jurisdictions responded to MDE's questionnaire on LIB recycling. Of those that responded, 16 (Allegany, Baltimore City, Calvert, Caroline, Carroll, Cecil, Charles, Kent, Harford, Howard, Montgomery, Queen Anne's, Somerset, St. Mary's, Talbot, and Wicomico) accept LIBs for recycling either full time or as part of their HHW collection programs. Cost is the major reason counties reported not offering the service.

The nonprofit organization Call2Recycle partners with over 300 stewards (battery producers) to set up free collection stations for residents. Local drop-off locations can be found on Call2Recycle's website at www.call2recycle.org. Organizations can join Call2Recycle to participate in the program. Call2Recycle has collected over 30 million pounds of LIBs since its inception in 1994.

The above collection opportunities are primarily intended for residences. Some private collection companies may accept batteries from both residential and commercial sources. Maryland's Recycling Market Directory lists recyclers for batteries and electronics. Automobile manufacturers take back LIBs used in their electric and hybrid cars.

Once batteries are collected, they must be sorted and processed. LIB sorting and recycling facilities exist in the U.S. and abroad. For example, Call2Recycle uses the following facilities for LIBs generated in the U.S.:

**Sorters**
Battery Solutions, Howell, Michigan
INMETCO, Ellwood City, Pennsylvania
Battery Solutions, Mesa, Arizona
Wistron GreenTech, McKinney, Texas

**Processors**
Glencore / Xstrata, Sudbury, Ontario (Canada)
Toxco/ Retriev, Trail, British Columbia (Canada)
UMICORE, Hoboken, Belgium
SungEel Hitech, South Korea
Recycling Coordinators, Akron, Ohio
RetrievTechnologies, Lancaster, Ohio

Additional companies are in various stages of implementing their own LIB recycling processes. For example, LiCycle, a company based in Ontario, Canada, states that its process recovers 80 to 100% of materials in LIBs. Blue Whale Materials is seeking to establish a LIB recycling facility in the U.S.

**LIBs and MRA**
MRA requires each county to adopt a plan to reduce the solid waste stream by 20 or 35% by recycling, depending on population. MDE also has a statewide voluntary goal of 55%. When determining what constitutes a recyclable material that counts towards a county's mandated recycling rate (MRA recyclable), MDE considers the following definitions:

Recyclable Materials (Section 9-1701(p) of the Environment Article, Annotated Code of Maryland) includes "those materials that:
- Would otherwise become solid waste for disposal in a refuse disposal system; and
- May be collected, separated, composted, or processed and returned to the marketplace in the form of raw materials or products."

Recycling (9-1701(q) of the Environment Article, Annotated Code of Maryland) means "any process in which recyclable materials are collected, separated, or processed and returned to the marketplace in the form of raw materials or products."

Solid Waste Stream (9-1701(t) of the Environment Article, Annotated Code of Maryland) means "garbage or refuse that would, unless recycled, be disposed of in a refuse disposal system."
- "Solid waste stream" includes organic material capable of being composted that is not composted in accordance with regulations adopted under § 9-1725(b) of this subtitle.
- "Solid waste stream" does not include:
  - Hospital waste;
  - Rubble;
  - Scrap material;
  - Land clearing debris;
  - Sewage sludge; or
  - Waste generated by a single individual or business and disposed of in a facility dedicated solely for that entity's waste."

Since they would otherwise be solid waste for disposal in a refuse disposal system, batteries, including LIBs, are considered a MRA recyclable material and count towards a county's mandated recycling rate.

## Steps to Create a Statewide LIB Recycling Program

As described above, some opportunities for the collection and recycling of LIBs currently exist, and as the materials in LIBs continue to increase in value, additional private recycling capacity for LIBs is likely to be developed in the U.S. and abroad. To encourage statewide recycling opportunities for LIBs, the state could promote and support these opportunities through a variety of methods described below.

### Promote and provide information on existing collection options

MDE currently administers the Statewide Electronics Program, oversees local recycling programs under the MRA, and coordinates the state agency recycling program. Furthermore, most counties throughout Maryland operate battery collection programs and most manufacturers accept batteries through their ecycling take back programs. As a result, MDE may be an appropriate entity to serve as a clearinghouse for information on opportunities for recycling LIBs as they develop. MDE could establish a separate LIB website to maintain information about LIB recycling, options for consumers and businesses, and case studies on LIB recycling. In promoting these opportunities, MDE could coordinate with local governments and Call2Recycle, as the current primary collection channels for LIBs in Maryland.

### Provide permitting guidance for prospective LIB recycling

As the market for materials reclaimed from LIBs increases and federal policies promote domestic investment in LIB recycling, Maryland could encourage siting of new recyclers in Maryland by providing permitting assistance.

Except for the regulatory requirements that apply to the management of hazardous process residuals from any industry, the controlled hazardous substance (CHS) regulations only require a battery recycling facility to obtain a CHS facility permit if the facility stores hazardous waste batteries before they are inserted into the recycling process. "Storage" in this case has been interpreted as holding batteries for more than 24 hours after they have been accepted at the facility. However, a recycler can establish a separate universal waste handler location to consolidate shipments of batteries at a location distinct from the recycling location, without triggering a CHS permit requirement as long as the batteries are not at the recycling facility for more than 24 hours prior to recycling. The recycling process itself is also excluded from hazardous waste permit requirements.

MDE is currently developing recycling facility regulations as directed by Chapter 376 of 2017. The law directs MDE to adopt regulations to specify when a "recycling facility" may operate without a refuse disposal permit, and to exempt certain materials that are managed at a recycling facility from being designated as "solid waste." As part of these regulations, MDE could clarify the circumstances under which a LIB recycler (or other battery recycler) may operate without a refuse disposal permit.

For certain other types of recycling facilities, such as composting and anaerobic digestion facilities, MDE has published the permitting requirements within different areas of MDE and other agencies, which can assist prospective recyclers in more easily determining what is required and in obtaining contact information for each potential permitting requirement. It is particularly useful for types of facilities, such as LIB recycling facilities, that do not currently exist in Maryland and for which there might otherwise be a perception of uncertainty in the regulatory process. MDE could create such a guidance document for LIB battery recycling. Additionally, MDE's Resource Management Program, which handles recycling, could serve as a single point of contact for MDE to provide permitting assistance for prospective LIB recyclers. For example, the Resource Management Program could set up permitting meetings to pull together multiple permitting programs within MDE to advise prospective recyclers on regulatory requirements.

**Support innovation, research, and demonstration of LIB recycling technology**
Demand for LIB recycling is likely to increase rapidly in the coming years and businesses will be working to identify more efficient ways of recovering materials from LIBs. Maryland could provide targeted assistance through existing programs, such as the University of Maryland's Maryland Industrial Partnerships (MIPS) and MTech Ventures programs, to support research, development, and entrepreneurship in this area. MIPS provides grant funding to companies to conduct research projects that help those companies create new products. MTech Ventures is a technology incubator that helps technology-based start-up companies. In addition to these two programs through the University of Maryland, MDE could work with the Maryland Department of Commerce to identify any existing business assistance programs that could be used to assist local governments and prospective LIB recycling companies that may be interested in locating in Maryland.

**Supplement and enhance local collection programs**
As LIB recycling technologies and facilities expand in the U.S. and abroad, there may be a need for assistance in the collection of LIBs to achieve statewide coverage. There are several forms that a LIB collection program could take. LIBs could be collected through collection kits. The kits would allow an entity (e.g., local government, state, business, etc.) to safely wrap and package batteries in designated buckets, which would then be sent to a recycler once the buckets are full. The second scenario would include collection points throughout the state that are serviced by a collection contractor, such as the Maryland Environmental Service. Either system would require securing collection locations either through partnerships or establishing new drop-off locations. An outreach campaign would be necessary to ensure the proper collection of the batteries and prevent contamination of the material collected. Insurance may also be required on the locations in the event of a fire or other problem.

Finally, the state or private recyclers could supplement the counties' HHW programs with the stipulation that LIBs are collected year-round and recycled (as opposed to properly disposed) as part of the program. This would have the benefit of using already established collection points and eliminating the need to develop and operate a completely new program. Additionally, by supplementing county HHW programs, the counties may be able to sustain their current HHW programs and offer the collection of other materials that may, if improperly managed, be detrimental to the environment.

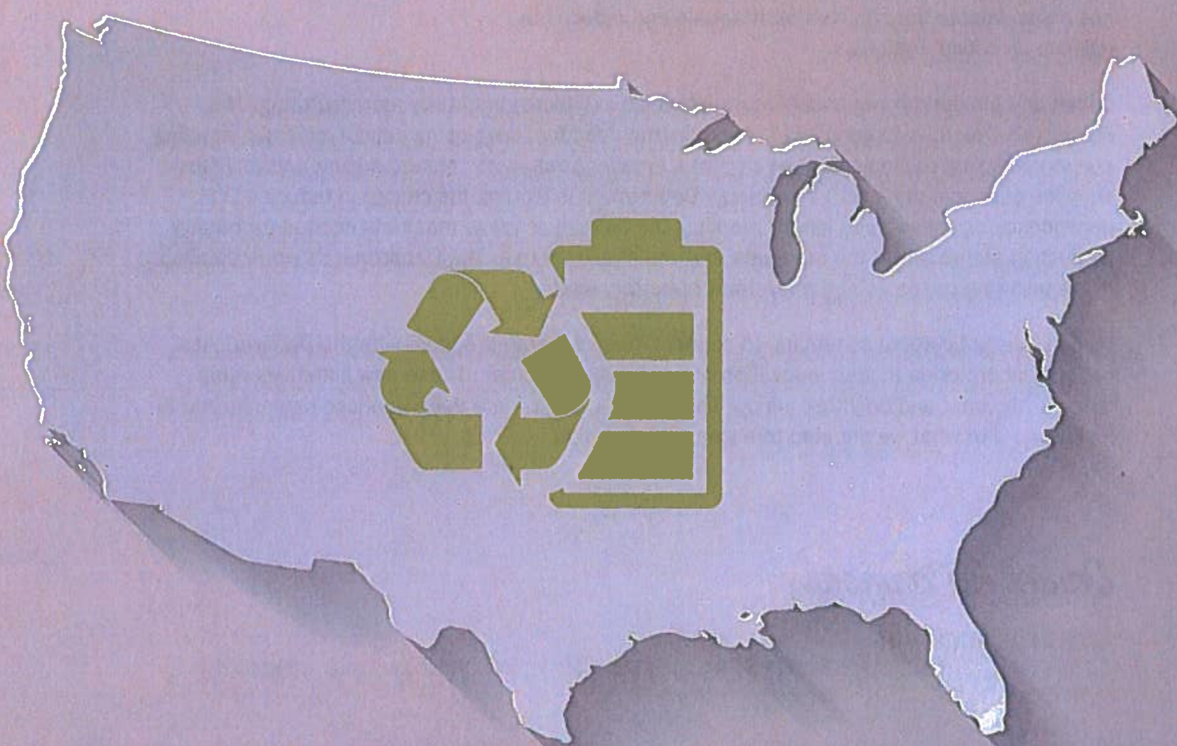
**Conclusion**

Each of the above collection methods would involve costs for labor, packing materials, maintenance of the collection locations, and outreach. All of which would require additional funding and personnel. In addition to providing funding for these costs, a challenge to implementing an effective statewide collection program will be in ensuring availability of service in all areas of the state, including more remote or rural areas. To minimize additional costs, the most efficient option would take advantage of existing collection locations through the Call2Recycle program and local HHW drop-off locations, potentially supplemented with additional locations for areas not currently served by either of these options. Local governments and industry would be part of providing recycling for LIBs.

U.S. DEPARTMENT OF ENERGY
OFFICE OF ENERGY EFFICIENCY AND RENEWABLE ENERGY

# Vehicle Technologies Office's
# Research Plan to Reduce, Recycle, and Recover Critical Materials in Lithium-Ion Batteries

June 2019



U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

VEHICLE TECHNOLOGIES OFFICE
ADVANCED MANUFACTURING OFFICE

## A MESSAGE FROM THE ASSISTANT SECRETARY

Research is at the heart of American innovation. The scientific research at the U.S. Department of Energy's national labs, along with collaborations with academia and industry, have fueled many advancements over the years.

Our extensive battery research and development (R&D) is only one example of how the Energy Department's breakthroughs have led to benefits for American consumers and businesses. From consumer electronics to national defense, lithium-ion batteries power our daily lives. Over the past 10 years, the Energy Department's commitment to battery R&D has reduced the cost of lithium-ion batteries by 80%, lowering the cost of electric vehicle battery packs to $197/kWh. To continue driving down costs for consumers and businesses, we must ensure that the United States has a sustainable supply chain of materials and reduce our reliance on critical materials.

Cobalt and lithium are two critical materials used in lithium-ion battery manufacturing. The President's Executive Order 13817 identifies the need for "developing critical minerals recycling and reprocessing technologies" as part of a broader strategy to "ensure secure and reliable supplies of critical minerals." The Energy Department is leading the charge in reducing U.S. dependence on these materials by reducing the amount of these materials needed for battery production and recycling the materials that are already in use. The Department's work, detailed in the following pages, is at the forefront of battery R&D.

I am enthusiastic about continuing to connect American entrepreneurs with the Department's national laboratories to spur innovation and leverage resources. These new initiatives bring together the best and brightest minds. There is no greater force than American ingenuity and I look forward to what we are able to accomplish together.

*Daniel R Simmons*

**DANIEL R SIMMONS**
ASSISTANT SECRETARY FOR ENERGY EFFICIENCY AND RENEWABLE ENERGY
U.S. DEPARTMENT OF ENERGY

# **REDUCING DEPENDENCE** OF LITHIUM-ION BATTERIES on Critical Materials

Lithium-ion batteries have become the main choice for portable electronics (such as smart phones, tablets, and laptops), power tools, and electric vehicles (EV) for personal, commercial, industrial, and military applications. The demand for lithium-ion batteries for EVs is expected to grow as the cost of manufacturing and materials is reduced while performance improves. The U.S. Energy Information Administration (EIA) projects that U.S. light-duty battery EV sales will reach 1.3 million by 2025 and others project even higher sales growth.[1,2] Global EV sales are expected to reach 30 million by 2030, up from 1.1 million in 2017.[3] This growth in EV sales, as well as increased demand for consumer and stationary uses, are expected to double the demand for lithium-ion batteries by 2025 and quadruple the demand by 2030.[3]

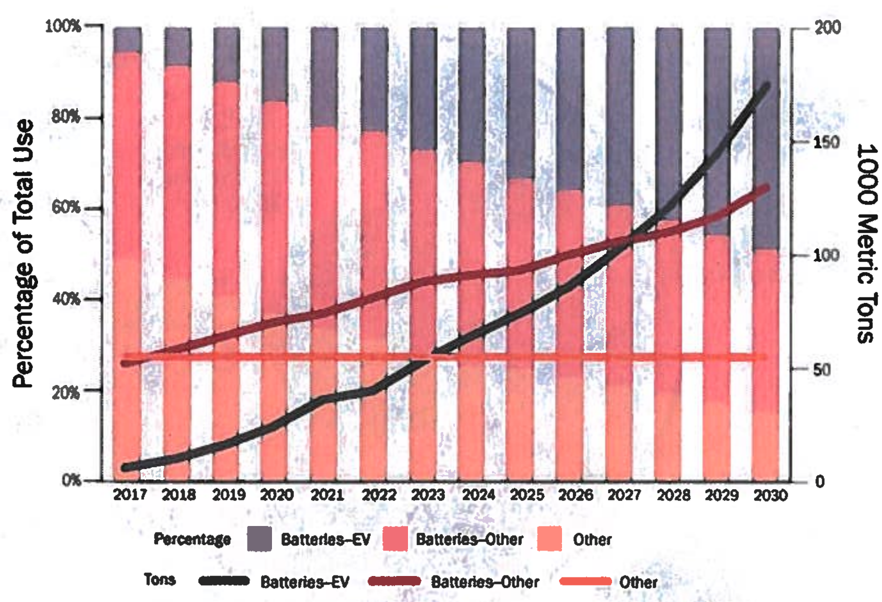
Demand for global production of battery materials, such as lithium, cobalt, manganese, nickel, and graphite, will grow at similar rates. In fact, the growth in demand for lithium-ion batteries for EVs will establish EVs as the largest end-user of cobalt and lithium, and could create a particularly high supply risk for cobalt.[4] In general, the U.S. Department of Energy (DOE) assesses material criticality based on importance to energy and the potential for supply risk for a range of energy technologies.

In response, DOE work is based on three pillars: 1) diversifying global supply chains to mitigate supply risk; 2) developing material and technology substitutes; and 3) promoting recycling, reuse and more efficient use to significantly lower global demand for critical materials. The DOE approach to critical materials is in alignment with the President's Executive Order 13817 to ensure secure and reliable supplies of critical minerals.

The DOE Vehicle Technologies Office (VTO), within the Office of Energy Efficiency and Renewable Energy (EERE), supports early-stage research to significantly reduce the cost of EV batteries while reducing battery charge time and increasing EV driving range. Over the past 10 years, VTO research and development (R&D) has lowered the cost of EV battery packs by 80% to $197/kWh in 2018.[5] Current battery technology performance is far below its theoretically possible limits. Near-term opportunities exist to develop innovative technologies that have the potential to significantly reduce battery cost and achieve the operational performance needed for EVs to achieve cost competitiveness with gasoline vehicles.

**Forecasted Global Cobalt Demand by End-Use**

*Source: NREL analysis of Bloomberg New Energy Finance, 2018**




**https://www.bloomberg.com/news/articles/2018-06-10/cobalt-battery-boom-wavers-as-china-demand-lull-brings-out-bears*

1 EIA Annual Energy Outlook 2019, https://www.eia.gov/outlooks/aeo/pdf/aeo2019.pdf
2 https://about.bnef.com/electric-vehicle-outlook/
3 http://cii-resource.com/cet/AABE-03-17/Presentations/BRMT/Pillot_Christophe.pdf
4 https://about.bnef.com/electric-vehicle-outlook/
5 Steven Boyd, Vehicle Electrification, Presented at DOE Vehicle Technologies, Annual Merit Review, June 2018, Washington, D.C

**President's Executive Order 13817:**

Critical materials such as lithium and cobalt are both expensive and dependent on foreign sources for production. The President's Executive Order 13817* identifies the need for "developing critical minerals recycling and reprocessing technologies" as part of a broader strategy to "ensure secure and reliable supplies of critical minerals."

*https://www.whitehouse.gov/presidential-actions/presidential-executive-order-federal-strategy-ensure-secure-reliable-supplies-critical-minerals/

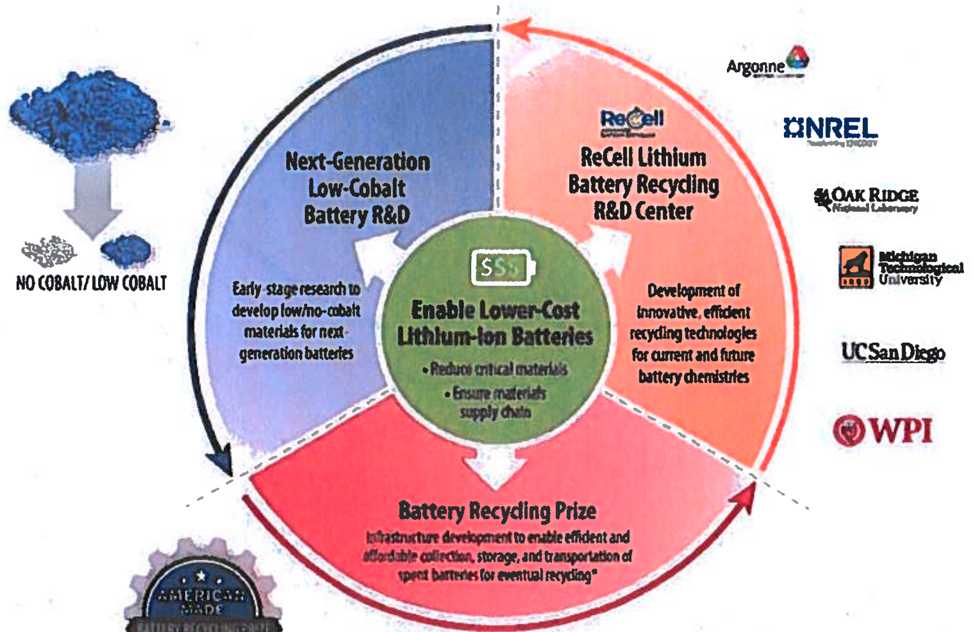
To mitigate potential lithium-ion battery critical materials supply risks, DOE has established the following goal:

**By September 2022, reduce the cost of electric vehicle battery packs to less than $150/kWh with technologies that significantly reduce or eliminate the dependency on critical materials (such as cobalt) and utilize recycled material feedstocks.**

To achieve this goal and address potential critical materials issues, VTO will support 3 key areas of R&D.

- Supporting laboratory, university, and industry research to develop low-cobalt (or no cobalt) active cathode materials for next-generation lithium-ion batteries.
- Establishing the ReCell Lithium Battery Recycling R&D Center focused on cost-effective recycling processes to recover lithium battery critical materials.
- Launching a Lithium-Ion Battery Recycling Prize to incentivize American entrepreneurs to find innovative solutions to solve current challenges associated with collecting, storing, and transporting discarded lithium ion batteries for eventual recycling. This will be accomplished by a prize structure allowed under the America COMPETES Act. VTO will coordinate with DOE's Advanced Manufacturing Office on the Prize.

## Critical Materials Research Plan for Batteries




* Funded by the U.S. Department of Energy Vehicle Technologies Office, within the Office of EERE, in collaboration with the Advanced Manufacturing Office, and administered by the National Renewable Energy Laboratory

▶ LITHIUM BATTERY CRITICAL MATERIAL **REDUCTION INITIATIVE**

# Charting a Course to **Reduce or Eliminate Cobalt in Lithium-Ion Batteries** for Electric Vehicles

Cobalt is one of the most common materials found in lithium-ion battery cathodes and plays an important role in stabilizing the cathode while the battery is in operation. The Democratic Republic of Congo supplies nearly 58% of the world's cobalt and 80% of that supply goes to China. China is the world's leading producer of refined cobalt and a leading supplier of cobalt imports to the United States.[6]

The mining practices in Congo have been of concern because of a lack of environmental safeguards, labor, health issues, and political uncertainty. These factors may limit the availability of cobalt to the supply chain and increase its demand, leading to rapid price increases in lithium-ion batteries. Cobalt is considered the highest material supply risk for EVs in the short- and medium-term.[3]

Reducing the amount of cobalt in lithium-ion batteries for EVs by substituting it with other materials has been a major focus within VTO's R&D portfolio. The first generation of lithium-ion batteries for consumer electronics contained cathodes with 60% cobalt. The first generation of EV batteries contained 33% cobalt in cathodes, while current commercial cathodes in EV batteries contain 15-20% cobalt, and industry is actively developing 10% cobalt cathodes.

Even if cobalt amounts in EV batteries are reduced to 10%, there is still a potential supply shortage of cobalt if EV penetration grows as expected. To support further reducing cobalt content in EV batteries, VTO launched over $50 million of competitively selected laboratory, university, and industry research projects.[7] These projects will develop low cobalt (or no cobalt) active cathode materials for next generation lithium-ion batteries over the next three years. Some of VTO's newest major research initiatives include:

**Reducing cobalt in cathodes to less than 5% weight:** University, industry, and national lab research in next generation cathodes focused on reducing cobalt content much below the current state-of-the-art cathodes while continuing to improve cathode material performance in EV batteries. Projects will focus on developing high energy capacity materials at high voltages using nickel-manganese based materials with cobalt substitution.

**Cobalt-free disordered rock-salt structured materials:** A multi-laboratory research consortium led by Lawrence Berkeley National Laboratory will explore cathodes based on completely novel material compositions with no cobalt fabricated using experimental processing techniques and first principle modeling.

**Significance and Impact**

Create critical material-free cathode materials that offer equal or greater performance in EV batteries at lower cost by 2022.

6 USGS Mineral Commodities Summary 2018 https://minerals.usgs.gov/minerals/pubs/mcs/2018/mcs2018.pdf
7 https://www.energy.gov/articles/department-energy-announces-80-million-investment-advanced-vehicle-technologies-research

▶ ReCell LITHIUM BATTERY **RECYCLING R&D CENTER**

# Affordably Recover and Re-Use Lithium Battery Critical Materials

### Significance and Impact

Creating batteries that utilize completely recycled components that have similar performance to critical materials will further diversify the EV battery supply chain and make it less reliant on critical materials.

Lithium-ion battery cathodes can be made from more than 15 different cathode chemistries. While this variety of chemistries enables lithium-ion batteries to be used in many applications, it also increases material demand. This demand creates material value for end-of-life batteries in EVs and consumer electronics. As new chemistries become commercially available, the need arises to develop flexible and reliable processes to maximize economic value to the recycler. Advanced recycling approaches can significantly reduce the demand for imported critical materials.

VTO is investing in early-stage research to develop recycling technologies for extraction and reuse of the main components and materials in lithium-ion batteries that have lower energy and environmental impacts. As part of this investment, VTO is establishing the ReCell Lithium Battery Recycling R&D Center focused on cost-effective recycling processes to recover lithium battery critical materials. The ReCell Center will be led by Argonne National Laboratory along with the National Renewable Energy Laboratory, Oak Ridge National Laboratory, and three universities. The team's work consists of the following four research areas that are supported by economic/process modeling and supply chain analysis, and will focus on developing innovative and efficient recycling technologies for current and future battery chemistries.

## ReCell LITHIUM BATTERY RECYCLING R&D CENTER RESEARCH AREAS

### Design for Recycling

Current battery packs are not assembled and materials are not chosen based on how efficient it would be to recover the material. This can often lead to increased recycling costs. Exploring novel materials and methods of designing battery packs and cells to decrease recycling costs without impacting battery performance has the potential to maximize profitability of recycling processes.

### Recovery of Other Materials

Though the cathode is the most expensive component of the battery, there are other components that, if recovered, could increase the value of end-of-life batteries. Recovery of the graphite anodes, electrolyte, and electrode sheets could create even more value out of spent batteries.

### Direct Recycling or Cathode-to-Cathode Recovery

The cathode of lithium batteries is the most expensive component and often contains the critical material cobalt. Current commercial recycling profitability depends on recovery of cobalt at an elemental level. If processes could recover cobalt at the cathode level, it would increase the value of end of life lithium batteries substantially.

### Reintroduction of Recycled Materials

Battery materials and cells for electric vehicles have strict performance and safety standards that need to be met before they are used in electric vehicles. Research projects will have cells built with recycled materials and tested to ensure they meet the performance standards of electric vehicles.

**LITHIUM-ION BATTERY RECYCLING PRIZE**

# **Innovative Solutions** to Enable Safe and Affordable Collection, Sorting, Storage, and Transport of Spent Lithium-Ion Batteries

Currently, lithium-ion batteries are only collected and recycled at a rate of less than 5%.[8] Recycled material could potentially provide one-third of United States cathode material needs for lithium-ion batteries by 2030.[7]

**Significance and Impact**

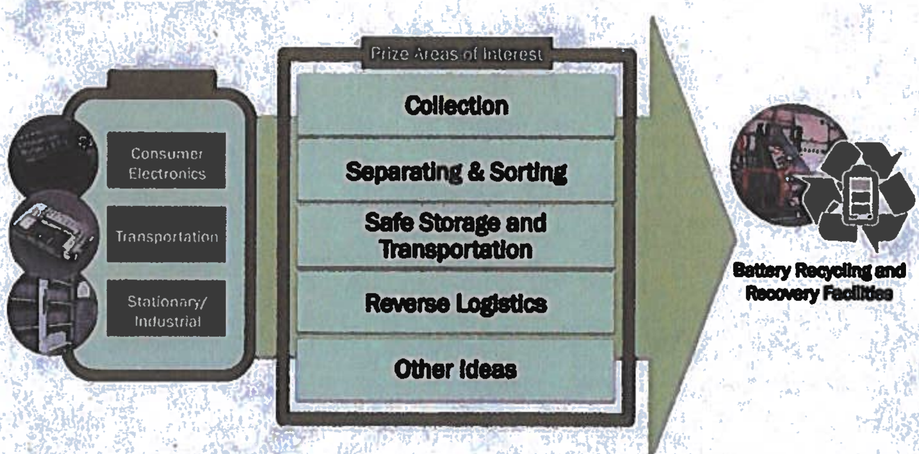
Accelerated efforts to create cost-effective, disruptive solutions to collect, sort, store, and transport 90% of spent or discarded lithium-ion batteries for eventual recycling.

The current recycling supply chain for collecting, sorting, storing, transporting, and recycling of lithium-ion batteries is limited, particularly for larger batteries used in EVs and industrial applications. VTO, in collaboration with DOE's Advanced Manufacturing Office, has established the Lithium-Ion Battery Recycling Prize.

The $5.5-million DOE Lithium-Ion Battery Recycling Prize is designed to incentivize American entrepreneurs to find innovative solutions to solve current challenges associated with collecting, sorting, storing, and transporting spent or discarded lithium-ion batteries for eventual recycling. The Lithium-Ion Battery Recycling Prize will be implemented in three progressive phases and will progress from concept to prototype and partnering to pilot validation. The goal of the Prize is to develop innovative business and technology strategies with the potential to capture 90% of all lithium-ion battery technologies (consumer electronics, industrial, stationary, and transportation applications) in the United States.

The prize will facilitate our nation's entrepreneurs to leverage DOE's connections to create new solutions and develop them into early-stage prototypes and processes. Successful concepts must consider cost-effective technologies such as separation and sorting of various collected battery types and sizes; rendering lithium-ion batteries safe or inert; or reducing the hazardous classification of lithium-ion batteries in order to reduce shipping costs.

In each phase, submissions will be evaluated by expert reviewers and a federal consensus panel. The DOE's National Renewable Energy Laboratory will be the Prize Administrator.




## COMPARING METAL PRODUCTION FROM NATURAL RESOURCES AGAINST RECYCLING FROM SPENT BATTERIES:

### COBALT

There is a significant amount of energy and water needed for production of cobalt from ore leading to a significant amount of $CO_2$ release.[9] The amount of energy and water needed for recovery of cobalt from collected and recycled lithium-ion batteries is expected to be significantly less.


8 https://www.call2recycle.org/

9 Q. Dai, J. C. Kelly, and A. Elgowainy. Cobalt Life Cycle Analysis Update for the GREET Model. September 2018. https://greet.es.anl.gov/publication-update_cobalt with data summary extraction by A. Mayyas and D. Steward of NREL

June 2019

*Photos on page 7 from iStock:*
*Upper graphic: 970445392, 1003888508, 1085157768, 174627960, 152941176, 542301166, 539816016, 891531576, 149161103, 891753858, 533516913, 500173777, 910873300, 530202998*

*Lower graphic: 149161103, 185517030, 539816016, 624098272, 813284388*

---

The mission of the **Office of Energy Efficiency and Renewable Energy (EERE)** is to create and sustain American leadership in the transition to a global clean energy economy. Its vision is a strong and prosperous America powered by clean, affordable, and secure energy.

The U.S. Department of Energy's **Vehicle Technologies Office** provides low cost, secure, and clean energy technologies to move people and goods across America.

The **Advanced Manufacturing Office** is the only technology development office within the U.S. Government that is dedicated to improving the energy and material efficiency, productivity, and competitiveness of manufacturers across the industrial sector.

U.S. DEPARTMENT OF ENERGY | Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

VEHICLE TECHNOLOGIES OFFICE
ADVANCED MANUFACTURING OFFICE

DOE/GO-102019-5147

Heliyon 5 (2019) e01866 ATTACHMENT 2

Contents lists available at ScienceDirect

Heliyon

journal homepage: www.heliyon.com

ELSEVIER

Heliyon

Review Article

# Lithium battery reusing and recycling: A circular economy insight☆

Mario Pagliaro [a,*], Francesco Meneguzzo [b]

[a] Istituto per lo Studio dei Materiali Nanostrutturati, CNR, via U. La Malfa 153, 90146, Palermo, Italy
[b] Istituto di Biometeorologia, CNR, via G. Caproni 8, 50145, Firenze, Italy

ARTICLE INFO

Keywords:
Energy
Lithium-ion battery
Battery recycling
Battery electric vehicle
Circular economy

ABSTRACT

Driven by the rapid uptake of battery electric vehicles, Li-ion power batteries are increasingly reused in stationary energy storage systems, and eventually recycled to recover all the valued components. Offering an updated global perspective, this study provides a circular economy insight on lithium-ion battery reuse and recycling.

## 1. Introduction

Driven by the electric vehicle (EV) boom [1], which led to a 3-fold increase in the price of lithium [2] and a 4-fold increase in that of cobalt [3] between 2016 and 2018, reclaiming lithium, cobalt, manganese and nickel (along with other valued materials like copper, aluminum and graphite) from spent lithium ion batteries has lately become profitable. Perhaps not surprisingly, numerous new lithium battery recycling plants started operation across the world, and those existing are expanding capacity.

In about 2 years, the recycling of lithium batteries which still in 2016 was claimed in Europe to lack economic viability as "only 3% of the material mix in batteries is made of lithium" [4], became profitable and convenient.

Investments started to flow targeting opportunities not only for recycling but also for refurbishing and reusing retired EV lithium-ion batteries (LIBs) in energy storage systems. "Certain companies" reads a working document of the European Commission dated mid 2018, "have already begun investing in recycling of used EV batteries in Europe (e.g. in Belgium and in France). Some have teamed up with car manufacturers to collect and recycle batteries" [5].

Hence, as lately emphasized by Melin, a reputed consultant in lithium-ion battery life cycle, "when it is not rare to read about recycling rates of 3 or 5 per cent… 58 per cent will be recycled this year" [6].

The environmental and economic benefits of LIB recycling are significant. As the lithium-ion recycling industry consolidates and the demand for spent LIBs increases, the old practice for which small batteries used by portable electronic devices were hazardously stockpiled in generic materials recovery facilities causing fires due to thermal runaway from damaged or short circuited batteries [7], will become a thing of the past.

This trend, we argument in this study, will further evolve and eventually first generation LIB recycling processes will be replaced by green chemistry processes producing highly pure ("battery-grade") lithium, cobalt and manganese compounds along with graphite, copper and aluminum.

Recycling, in general, relies on first generation recovery technologies in which a physical treatment to obtain different streams of raw materials is followed by a hydrometallurgical process (leaching and extraction) to extract metals [8].

Lithium-ion batteries, indeed, generally use a graphite anode and a cathode made of lithium metal oxides generally comprised of lithium-iron phosphate (LFP), lithium-nickel manganese cobalt (NMC), lithium nickel cobalt aluminum oxide (NCA), lithium-manganese oxide (LMO), or lithium-titanate oxide (LTO). First generation LIBs mainly used in portable electronics used lithium-cobalt oxide (LCO) [9].

The battery cells are assembled in modules and modules further assembled in battery packs. The voltage from "power" batteries supplying current to the motor of electric passenger cars or buses, can respectively top 300 V or even exceed 600 V.

☆ This study is dedicated to Dr Maria Lea Ziino for all she has done for the health of younger generations in 20 years of child psychology work carried out in Sicily.

* Corresponding author.
E-mail address: mario.pagliaro@cnr.it (M. Pagliaro).
URL: http://www.qualitas1998.net (M. Pagliaro).

https://doi.org/10.1016/j.heliyon.2019.e01866
Received 13 May 2019; Received in revised form 27 May 2019; Accepted 29 May 2019

Offering an updated global perspective, this study provides a circular economy insight on lithium-ion battery reuse and recycling.

## 2. Main text

### 2.1. Technology and chemistry aspects

By weight percentage (g material/g battery), a typical lithium-ion battery comprises about: 7% Co, 7% Li (expressed as lithium carbonate equivalent, 1 g of lithium = 5.17 g LCE), 4% Ni, 5% Mn, 10% Cu, 15% Al, 16% graphite, and 36% other materials [10].

Besides so called "calendar ageing", a lithium-ion battery becomes "spent" (reduced ability to store and deliver electricity) mainly because during the charge and discharge cycles taking place in the battery cells a solid product forms due to reaction of the lithiated anode with the alkyl carbonate comprising the electrolyte solution [11].

The resulting solid electrolyte interphase mainly consisting of stable (such as $Li_2CO_3$) and metastable components (polymers, $ROCO_2Li$, $(CH_2OCO_2Li)_2$, and ROLi prone to decompose exothermically at >90 °C, releasing flammable gases and oxygen) [7] progressively deposits on the anode surface forming a passivating film. This film limits the electrochemical reaction by making graphite sites inaccessible for $Li^+$ to intercalate and thus leading to an increase in internal ohmic resistance.

A typical EV lithium ion battery pack has a useful first life of 200,000–250,000 km [12], even though increasingly adopted fast-charging at >50 kW reduces the battery pack duration since battery degradation rapidly accelerates with charging current [13].

When, the automotive battery pack loses 20% (15% for certain EV models) of its initial capacity it becomes unfit for traction as the lower capacity of battery affects acceleration, range and regeneration capabilities of the vehicle [14].

#### 2.1.1. Second-life batteries

Besides the beneficial effect on the price of grid electricity due to the concomitant expansion of EVs utilization and renewable energy generation (particularly solar photovoltaics) [15], a second synergistic effect of battery electric vehicle on renewable electricity uptake lies in the possibility to reuse the batteries at the end of their automotive lifecycle for stationary energy storage, nicely fulfilling the key "refurbish, reuse, recycle" circular economy principle.

Compared to use in EVs, stationary applications demand lower current density from the battery pack. Hence, batteries retaining between 80-85% of their original capacity are collected. Battery modules found to have similar power and life are sorted out and re-assembled in new "repurposed" battery packs, ready for stationary usage [16], such as utility-scale grid, building and telecommunication tower storage.

A significant public demonstration of the ability of repurposed batteries to provide energy storage and grid services (regulation of the alternating current frequency in the grid) is the 3 MW (nominal power)/ 2.8 MWh (nominal capacity) energy storage system installed in 2018 at Amsterdam's "Joahn Cruyff Arena", (Fig. 1) [17].

During events at the stadium, the demand for electricity lighting, powering broadcasting, information technology equipment, catering, and security services increases from a baseload of around 200 kW to more than 3000 kW, for the entire duration of the event [17].

The new energy storage system installed at Amsterdam's Arena is comprised of 590 battery packs (340 new and 250 second-life batteries originating from EV 24 kWh battery packs whose original capacity is now slightly less than 20 kWh).

Directly supplied by the EV maker the second-life batteries are certified to last 10 years, namely the equivalent of batteries included in 148 used exemplars of the first generation world's best selling EV [18].

The batteries are contained in 61 battery racks (Fig. 2). Four bidirectional inverters manage the energy flows from the 4,200 rooftop PV modules, from and to the grid, and from the batteries to the stadium loads and to the grid (we remind that the grid accepts and supplies only alternating current, whereas the PV modules and the batteries supply direct current only).

The new energy storage system enables optimal use of both solar PV and grid electricity retrieved at low cost from the grid during the night hours.

Now the PV energy generated during the day, rather than being fed into the grid and sold to the grid operator at low price, goes to charge the 2.8 MWh battery pack whose nominal capacity was chosen to meet the energy demand from the stadium loads for 1 h during the most important events with maximum power absorption; and for 3 h when accessory services such as catering are not in use [17].

Flattening ("shaving" in the jargon used by electricity practitioners) the peak demand with free PV or low cost grid electricity stored in the lithium batteries *i)* cuts the diesel fuel cost (fuel is used in generators whose use is made compulsory from football authorities), *ii)* avoids peak demand charges, and *iii)* generates a revenue stream when the energy storage system is used to provide well paid grid-balancing services, such as frequency control.

Similar energy storage systems combining second-life EV battery modules with battery and power management digital technology for both residential, commercial and industrial applications are increasingly commercialized across the world by a number of companies.

Similarly, in China the world's biggest operator of telecommunication towers, since 2018 ended purchase of lead-acid batteries. All existing and rapidly ageing lead-acid batteries currently installed for back-up power at 98% of its 2 million telecom tower base stations (54 GWh battery storage demand) will be replaced by second-life LIBs [19]. Partnership agreements were signed with more than 16 EV and battery manufacturers, as second-life LIBs in 2018 were reported to be priced at less than \$100/kWh, namely the same price of new lead-acid batteries [19].

Fig. 1. Amsterdam's "Johan Cruyff Arena" multipurpose stadium. [Photo courtesy of Eaton].

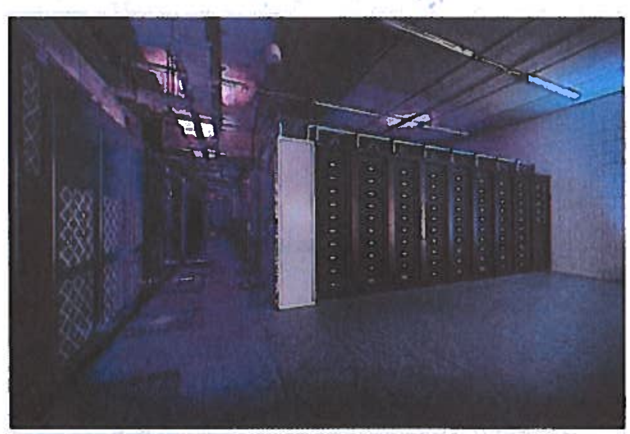


Fig. 2. Racks with part of the 2.8MWh energy storage system at the "Johan Cruyff Arena". [Photo courtesy of Eaton].

For comparison, this translates into forthcoming demand for up to 2 million retired EV batteries only from China's telecom base station back-up, since one single tower needs about 30 kWh back-up battery [19].

According to a thorough analysis conducted in 2017 by Melin, by 2025 about 75 per cent spent EV batteries will be reused in second-life solutions for several years after retirement from vehicles, after which they will be sent to recycling to recover all the valued components [20].

#### 2.1.2. *New green chemistry technologies*

Reviewing first-generation metal recovery processes using pyrometallurgical or hydrometallurgical methods, scholars in China lately emphasized the need for new "selective leaching of most of the valuable metals from the spent LIBs" [8].

Discovered in 2015, one such green process for the recovery of metals from spent Li-ion batteries makes use of citric acid ($H_3Cit$) and aqueous $H_2O_2$ affording Co and Li in excellent recovery yields (98% Co and 99% Li) [21].

In detail, the spent batteries are first discharged and then manually dismantled to recover the Al and Cu foils in metallic form and the separator, directly recycled after dismantling (Fig. 3).

The waste cathode materials ground into finer fractions for the subsequent extraction process is obtained by calcining at 700 °C for 2 h the cathode materials to remove carbon.

The powder of cathode material thereby obtained is used as raw material for the leaching process under optimized and mild extraction conditions (80 min, 70 °C, 2.0 M $H_2O_2$, with reductant dosage of 0.6 wt %, and slurry density of 50 g/L).

Aqueous $H_2O_2$ acts as clean reductant during metal leaching (Eq. 1), with both metal ions and waste citric acid being simultaneously recovered by selective precipitation (unbalanced).

$$H_3Cit + LiCoO_2 + H_2O_2 \rightarrow Co_3(Cit)_2 + Co(HCit) + Co(H_2Cit)_2 + Li_3Cit + Li_2(HCit) + Li(H_2Cit) + H_2O + O_2 \quad (1)$$

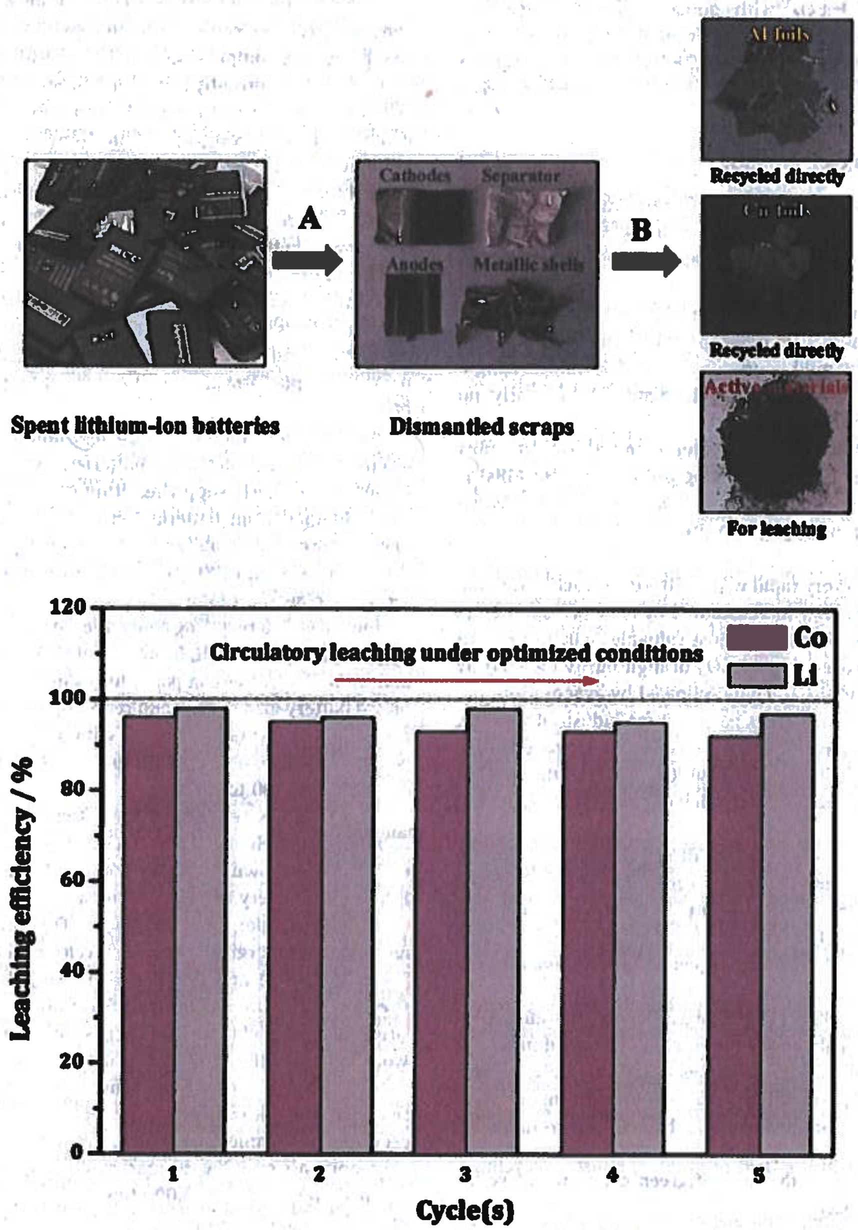



Fig. 3. Simplified pretreatment process of spent LIBs based on citric aicd/hydrogen peroxide oxidative leaching of Co and Li: (A) manual dismantling; (B) peeling off Al/Cu foils and recycling of Al and Cu (*top*); and circulatory leaching experiments under the optimized conditions using citric acid and $H_2O_2$ (*bottom*). [Reproduced with permission from Ref.21, Copyright American Chemical Society].

Co and Li ions dissolved in the lixivium are treated with oxalic acid and phosphoric acid solutions to recover Co and Li. The total reaction equation (Eq. 2) shows that water and oxygen are the only byproducts in the whole recovery process (unbalanced).

$$LiCoO_2 + H_2O_2 + H_2C_2O_4 + H_3PO_4 \rightarrow Co(C_2O_4)_2 + Li_3(PO)_4 + H_2O + O_2 \quad (2)$$

In a truly closed-loop route typical of the circular economy, about 99% Co and 93% Li could be recovered as $CoC_2O_4{\cdot}2H_2O$ and $Li_3PO_4$, respectively, whereas the recycled citric acid shows similar leaching capability as fresh acid (Fig. 3, bottom).

LFP batteries, we have discussed elsewhere [1], will remain for many years the dominating lithium battery technology used by electric vehicles. It is therefore particularly relevant the recent discovery of a green and economically viable process for recycling entire spent $LiFePO_4$ batteries to battery grade (99 wt%) $Li_2CO_3$ ready for manufacturing new LFP batteries [22].

The process is based on the selective leaching of lithium based on oxidation of $LiFePO_4$ to $FePO_4$ with aqueous sodium persulfate ($Na_2S_2O_8$), forcing lithium deintercalating from the cathode (Eq. 3), while neither Fe (0.048% leaching) nor P (0.387%) leach out from the cathode structure whose olivine crystal structure is fully retained during the lithium leaching process.

$$2LiFePO_4 + Na_2S_2O_8 \rightarrow 2FePO_4\downarrow + Li_2SO_4 + Na_2SO_4 \quad (3)$$

In detail (Fig. 4), cathode scrap of LFP powder attached on Al foil obtained by a local battery recycling company is first separated from soft-package batteries via discharging and dismantling, and then cut into small pieces.

More than 99% of Li is leached without the addition of acid and alkali under the optimal conditions of 1.05 times the stoichiometric amount of persulfate, under remarkably mild conditions (25 °C, 20 min stirring a 300 g $L^{-1}$ suspension of powdered cathode plates) with nearly no wastewater and solid waste generation.

No prior separation of cathode active material and Al foil (the most demanding procedure in the present recycling process of spent LIBs) is required because in the strong oxidative environment, Al is passivated (formation of a thin layer of $Al_2O_3$) resulting in an extremely low leaching of Al.

The leaching of lithium is very rapid with >90% of Li leached into the solution in only 5 min, an further increases to 99.8% by prolonging the leaching time to 20 min. As a result, the most valuable element in spent LFP batteries is directly recovered as $Li_2CO_3$ of high purity (>99%) by simple addition of $Na_2CO_3$ to the leachate followed by evaporation.

In a closed-loop method with great potential for industrial upscale, the mother liquor obtained after evaporation is used to prepare valued $Na_2SO_4{\cdot}10H_2O$ product via freeze crystallization, whereas the crystallized solution is returned to leach another batch of raw cathodes with the addition of fresh $Na_2S_2O_8$.

Besides Li recovery, the process enables direct cathode recycling to make new LFP cathodes for new batteries using the well-crystallized orthorhombic $FePO_4$ leaching residue whose XRD pattern is close to that of raw $LiFePO_4$ cathodes (the reverse of the phase transformation occurring in the charging of LFP battery, in which $LiFePO_4$ releases $Li^+$ ion and turns into $FePO_4$).

Affording highly pure (>99.5%) lithium carbonate, the aforementioned processes solve the main problem which so far has limited the industrial uptake of green chemistry processes in LIB recycling, namely the "lengthy processing and purification processes of the raw materials to reach battery grade" [23] which determines "the true cost to manufacture" [23] Li-ion batteries.

Practically useful research in the field of green chemistry recycling processes continues at fast pace.

Selected examples include the simultaneous recovery of Li and Co from $LiCoO_2$ cathode materials in a single step with good leaching efficiency (97% for Li and 98% for Co) using 0.6 M tartaric acid as leaching agent and 3% (v/v) $H_2O_2$ as reducatant (30 min at 80 °C with a solid to liquid ratio of 30 mL/g) [24]; and the recovery of all valuable metals from $LiNi_{0.5}Co_{0.2}Mn_{0.3}O_2$ cathode with excellent leaching efficiency (100% for Li, 93.38% for Ni, 91.63% for Co, and 92.00% for Mn) using an environmentally friendly leachant mixture of 0.2 M phosphoric acid and 0.4 M citric acid [25].

In the latter case, acid consumption is low, and the extraction time short (30 min at 90 °C with a solid to liquid ratio of 20 g/L) with no need for reductant as citric acid acts both as leachant and reductant.

### 2.2. Economic aspects

In a recent patent [10], seven main components (cobalt, lithium, copper, graphite, nickel, aluminum, and manganese) were reported to comprise >90% of the economic value of a spent lithium-ion battery: Co (39%) and Li (16%, as LCE equivalent) followed by Cu (12%), graphite (10%), Ni (9%), Al (5%) and Mn (2%).

The economic (and environmental) advantages of EVs are so large and significant (electric buses, for example) [26] that, regardless of rapidly growing output from new large factories in China, the demand of Li-ion batteries currently overcomes supply. This is especially the case for countries and regions like Europe where limited Li-ion battery manufacturing takes place. One Germany's bus manufacturer, for example, by early 2019 was reported to be unable to get the batteries needed to start manufacturing electric buses in 2020 [27].

New regulation in China now holds EV makers responsible for the recovery of batteries, requiring them to set up recycling channels and service outlets where old batteries can be collected, stored and transferred to recycling companies. By the end of February 2019, 393 carmakers, 44 scrapped car dismantling enterprises, 37 cascade utilization enterprises and 42 recycling enterprises had already joined the new traceability platform to track origin and owners of discarded batteries [28].

Furthermore, since 2017 new legislation forbids to import in China electronic waste, including batteries, which is leading China-based companies formerly supplying lithium carbonate, cobalt and nickel sulfates obtained from batteries retired from large consumer electronics manufacturers to establish new recycling plants "overseas" (in South Korea for example) [29]; as well as foreign EV battery makers to open recycling plants in China [30].

Industrial LIB recycling companies in China include Taisen Recycling, Zhejiang Huayou Cobalt, Brunp, Jinqiao Group, Jiangxi Ganfeng Lithium and GEM. The latter company, for example, operates in China 13 automated battery dismantling and recycling facilities where it manufactures the cathode precursors (Fig. 5), with an annual production capacity of cobalt, nickel materials of lithium ion batteries and cathode material exceeding 50,000 tons [31].

The products resulting from battery recycling are sold to battery manufacturers. Hence, it may not be surprising to learn that large battery manufacturers own recycling companies, as in the case of Brunp, a lithium-ion battery recycler in Hunan.

Though smaller, from Singapore (TES-AMM operating a plant using an hydrometallurgical process developed in France), through South Korea (SungEel) and Belgium (Umicore), from the U.S. and Canada (Retriev Technologies) through Australia (Envirostream Australia) and Great Britain (Belmont Trading), several other companies across the world operate LIB recycling facilities.

The list above is far from being exhaustive. What is relevant here is that, driven by dramatically growing uptake of LIBs for electric vehicles, recycling companies are rapidly expanding their facilities and new companies are entering the market. For instance, by early 2019 when the company recycled over 8,000 tons of retired batteries annually through an hydrometallurgical process, a Korean firm was undergoing a 5-fold expansion with three new plants due to start operations in Hungary, India, and in USA [32].

Market forecasts for the LIB recycling industry agree on significant

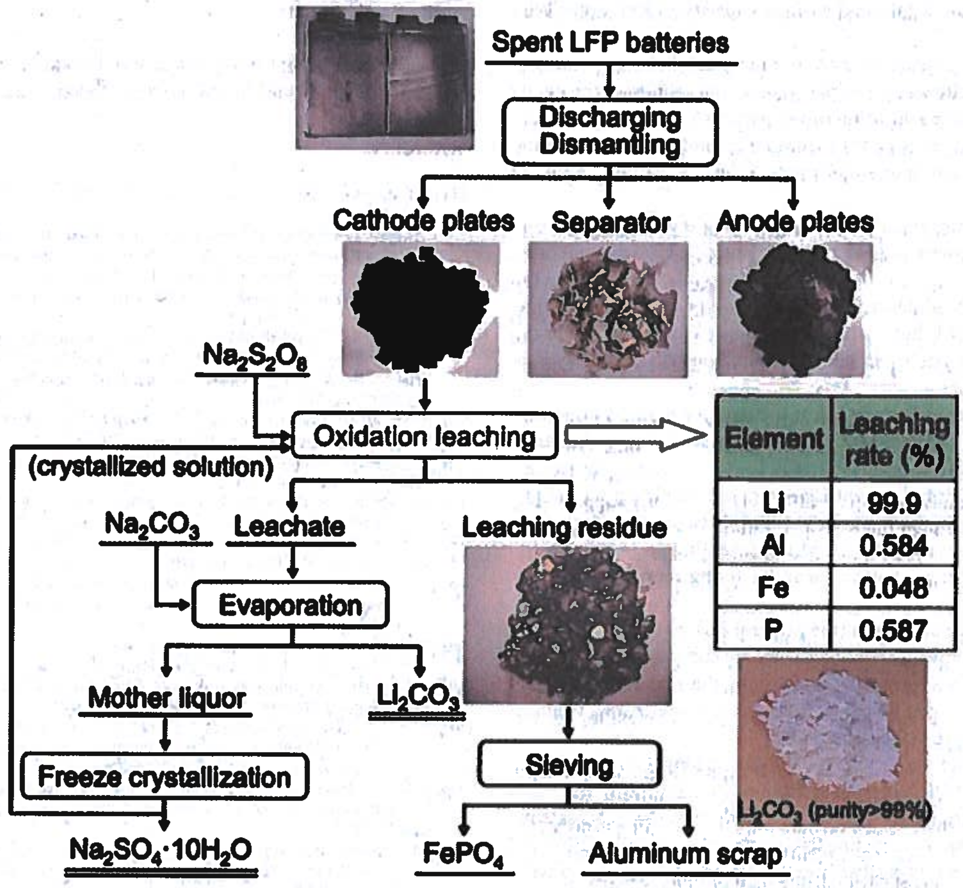



Fig. 4. Flowsheet of the method for treating entire spent $LiFePO_4$ batteries using aqueous sodium persulfate under neutral conditions for Li leaching. [Reproduced with permission from Ref.22, Copyright American Chemical Society].

growth, though forecasted figures vary. According to the aforementioned 2017 report [6, 33], recycled lithium will reach 9 percent of total lithium battery supply in 2025 (namely 5,800 tonnes of recycled lithium, or 30, 000 tonnes LCE), and that of cobalt almost 20 percent of the demand, with >66% lithium-ion batteries being recycled in China.

New green chemistry technology will further contribute to lower recycling costs. Amid the numerous green recovery processes, the battery recycling industry will uptake the cheapest and most versatile.

Indeed, upon developing the leaching process based on citric acid/ phosphoric acid [25], Zhou and co-workers compared it with two other efficient and rapid metal recovery processes in leaching $LiNi_xCo_yMn_zO_2$ cathode material, namely those using lactic [34] acid and hydrogen peroxide, and malic [35] acid and hydrogen peroxide.

The three processes have similar leaching temperature, solid to liquid ratio and leaching time. Assuming therefore to treat one ton of waste cathode materials, the difference in cost mainly stems from raw material prices, with the cost of the phosphoric acid/citric acid leaching process about 30% lower than the malic acid process, and approx. 38% lower than that using expensive lactic acid [25].

Low cost citric acid, indeed, is the single largest chemical obtained via biomass fermentation and the most widely employed organic acid [36].

## 3. Conclusions

In early 2017, Zhao published one of the first comprehensive books on the reuse and recycling of lithium-ion batteries [37]. Referring to the "uncertain performance and service life of retired power batteries", ending the "Market Development of Reuse and Recycling of Power Batteries" chapter, he wrote:

"The profit margin in the reuse of lithium-ion power batteries is unclear. Although data on batteries provided by lithium-ion power battery producers state that the batteries removed from new energy vehicles retain 70–80% valid energy and appear competitive in costs, there are still many challenges when energy storage is focused in the field of battery reuse" [38].

Two years later, a large electric power company started construction of a 268.6 MWh energy storage plant in the east China's Jiangsu Province. The PV + storage plant will use retired EV batteries of 75,000 kWh residual capacity (45,000 kWh from LFP batteries and 30,000 KWh from

Fig. 5. The automatic control system of GEM power battery precursor material production line. [Photo courtesy of GEM Co., kindly reproduced from gem.com.cn].

lead-acid batteries), with additional storage capacity of 193,600 kWh from new LIBs [39].

This single example renders the pace of innovation in energy storage (and renewable electricity storage in particular), and reinforces the need to broaden and renew the education of energy managers [40], particularly in the field of solar energy [41] whose 2018 photovoltaic output in China grew by 50 per cent in one year only, to the outstanding figure of over 177 TWh [42].

Regardless of ongoing reports for which, citing data going back to 2010, lithium-ion batteries would be "currently recycled at a meagre rate of less than 5% in the European Union" [43], this study not only refers to actual figures for which, globally, 58% of the world's spent LIBs will be recycled only in 2019 [6], but also shows evidence of a global boom of LIB industrial recycling lately extending to numerous countries beyond China.

This is not a research policy study but it cannot be omitted to notice how, reflecting global dominance of China's battery manufacturing and recycling industries, most research articles [21, 22, 24, 25, 34, 35] on the recovery of valued metals from spent LIBs were financially supported by China's government through the National Natural Science Foundation of China, and through Provinces interested in preventing pollution *and* in supporting the huge new battery manufacturing and battery EV industries.

There is not shortage of lithium (the mineral raw material) [44], but there is shortage of highly pure lithium carbonate and lithium hydroxide (the chemicals) as lately shown, for example, by the scarcity of battery grade lithium lately recorded by the Germany's company willing to start large-scale electric bus manufacturing [27].

In brief, the reuse and the recycling of LIBs is no longer an option but an inevitable need for both battery and battery EV manufacturers.

Helping to further streamline and automate the recycling process, the circular economy companies recycling lithium-ion batteries already work with battery makers to adopt easily dismantled product designs, and will shortly uptake the new green chemistry processes lately developed for the green recovery of all valued battery components.

Energy storage in lithium-ion battery is essential to expand the uptake of clean and renewable electricity for all energy needs including and foremost for powering electric vehicles. Providing an updated global perspective on lithium-ion battery reuse and recycling, this study will be useful to scholars, for example to update content of their teaching, as well as to policy makers devising new policies to promote the energy transition [45].

## Declarations

### *Author Contribution statement*

Mario Pagliaro, Francesco Meneguzzo: All authors listed have significantly contributed to the development and the writing of this article.

### *Funding statement*

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

### *Competing interest statement*

The authors declare no conflict of interest.

### *Additional information*

No additional information is available for this paper.

## Acknowledgements

We thank Michele De Gaspari, Eaton, for kindly sharing information about the "Joahn Cruyff Arena" energy storage system.

## References

[1] M. Pagliaro, F. Meneguzzo, The driving power of the electron, J. Phys. Energy 1 (2019), 011001.

[2] The price of 99% lithium carbonate in Chile, where it is mostly produced, went from slightly more thant $5,000/tonne as of Jan. 2016 to $15,000/tonne as of Sept. 2018. Data source: benchmark Mineral Intelligence, cit. in F. Els, the lithium price bulls were right, Mining, 30 November 2018. See at the URL: www.mining.com/lithium-price-bulls-right.

[3] The price of 99% cobalt in Congo, where it is mostly produced, went from slightly les thant $24,000/tonne as of Jan. 2016 to $80,000/tonne as of Jan. 2018. in E. Nelson, Price of cobalt, Quartz, February 2018. See at the URL: www.theatlas.com/charts/r1VKbCcwG.

[4] A. Vassart cit. In: P. Crompton, Closed Loop Lithium Battery Recycling Still Not Economical, bestmag.co.uk, 23 September 2016.

[5] European Commission, On Raw Materials for Battery Applications - SWD(2018) 245, Brussels, 17 May 2018.

[6] H.E. Melin, New Report on Recycling and Second Life of Lithium-Ion Batteries, linkedin.com, 21 June 2018.

[7] W. Lv, Z. Wang, H. Cao, Y. Sun, Y. Zhang, Z. Sun, Materials for lithium-ion battery safety, Sci. Adv. 4 (2018), eaas9820.

[8] W. Lv, Z. Wang, H. Cao, Y. Sun, Y. Zhang, Z. Sun, A critical review and analysis on the recycling of spent lithium-ion batteries, ACS Sustain. Chem. Eng. 6 (2018) 1504–1521.

[9] A. Yoshino, Development of the lithium-ion battery and recent technological trends, in: G. Pistoia (Ed.), Lithium-Ion Batteries, Elsevier, Amsterdam, 2014, pp. 1–20.

[10] A. Kochhar, T. G. Johnston, A Process, Apparatus, and System for Recovering Materials from Batteries, WO2018218358A1 (2018).

[11] J. Vetter, P. Novak, M.R. Wagner, C. Veit, K.-C. Möller, J. Besenhard, M. Winter, M. Wohlfahrt-Mehrens, C. Vogler, A. Hammouce, Ageing mechanisms in lithium-ion batteries, J. Power Source 147 (2005) 269–281.

[12] Y. Gao, J. Jiang, C. Zhang, W. Zhang, Z. Ma, Y. Jiang, Lithium-ion battery aging mechanisms and life model under different charging stresses, J. Power Source 356 (2017) 103–114.

[13] T.R. Hawkins, B. Singh, G. Majeau-Bettez, A.H. Strømman, Comparative environmental life cycle assessment of conventional and electric vehicles, J. Ind. Ecol. 17 (2012) 53–64.

[14] S. Saxena, C. Le Floch, J. MacDonald, S. Moura, Quantifying EV battery end-of-life through analysis of travel needs with vehicle powertrain models, J. Power Source 282 (2015) 265–276.

[15] L. Albanese, R. Ciriminna, F. Meneguzzo, M. Pagliaro, The impact of electric vehicles on the power market, Energy Sci. Eng. 3 (2015) 300–309.

[16] B. Sanghai, D. Sharma, K. Baidya, M. Raja, Refurbished and Repower: Second Life of Batteries from Electric Vehicles for Stationary Application, SAE Technical Paper 2019-26-0156, 2019.

[17] J. Robb, Making Stadiums and Arenas More Resilient and Energy Efficient, Publication No. WP701001EN/CSSC-868, Eaton xStorage Buildings White paper, March 2018.

[18] M. De Gaspari, Energy storage su building, Energy Management Conference, Milan, 26 October 2018.

[19] N. Jiao, China Tower Can 'absorb' 2 Million Retired Electric Vehicle Batteries, idtechex.com, 27 September 2018.

[20] H.E. Melin, Circular Opportunities in the Lithium-Ion Industry, Creation Inn, London, 2017.

[21] X. Chen, Ch. Luo, J. Zhang, J. Kong, T. Zhou, Sustainable recovery of metals from spent lithium-ion batteries: a green process, ACS Sustain. Chem. Eng. 3 (2015) 3104–3113.

[22] J. Zhang, J. Hu, Y. Liu, Q. Jing, C. Yang, Y. Chen, C. Wang, Sustainable and facile method for the selective recovery of lithium from cathode scrap of spent $LiFePO_4$ batteries, ACS Sustain. Chem. Eng. 7 (2019) 5626–5631.

[23] Battery University, BU-705a: Battery Recycling as a Business, 28 February 2019. See at the URL: https://batteryuniversity.com/learn/article/battery_recycling_as_a_business.

[24] X. Chen, D. Kang, L. Cao, J. Li, T. Zhou, H. Ma, Separation and recovery of valuable metals from spent lithium ion batteries: simultaneous recovery of Li and Co in a single step, Separ. Purif. Technol. 210 (2019) 690–697.

[25] L. Zhuang, C. Sun, T. Zhou, H. Li, A. Dai, Recovery of valuable metals from LiNi0.5Co0.2Mn0.3O2 cathode materials of spent Li-ion batteries using mild mixed acid as leachant, Waste Manag. 85 (2019) 175–185.

[26] M. Pagliaro, F. Meneguzzo, Electric bus: a critical overview on the dawn of its widespread uptake, Adv. Sustainable Syst. (2019) 1800151.

[27] MAN hat ein Batterieproblem, boerse.ard.de, 25 February 2019.

[28] China Building Traction Battery Recycling System as NEV Develops Fast, People's Daily Online, 28 February 2019.

[29] Chinese Lithium-Ion Battery Refinery Overcomes Logistics Barriers and Starts Global alliance, joc.com, 3 July 2018.

[30] J. Min-hee, SK Innovation to Enter Chinese EV Battery Recycling Market, businesskorea.co.kr, 29 November 2018.

[31] GEM, Waste Battery and Power Battery Material Recycling Industrial Chain. http://en.gem.com.cn/index.php/feijiudianchiheniefeiliao.
[32] SungEel MCC Americas Announces Lithium-Ion Battery Recycling Plant Location in New York State, prnewswire.com, 27 September 2018.
[33] Circular Energy Storage, Recycled Lithium to Reach 9 Percent of Total Lithium Battery Supply in 2025, circularenergystorage.com, London, 30 November 2017.
[34] L. Li, E. Fan, Y. Guan, X. Zhang, Q. Xue, L. Wei, F. Wu, R. Chen, Sustainable recovery of cathode materials from spent lithium-ion batteries using lactic acid leaching system, ACS Sustain. Chem. Eng. 5 (2017) 5224–5233.
[35] C. Sun, L. Xu, X. Chen, T. Qiu, T. Zhou, Sustainable recovery of valuable metals from spent lithium-ion batteries using DL-malic acid: leaching and kinetics aspect, Waste Manag. Res. 36 (2018) 113–120.
[36] R. Ciriminna, F. Meneguzzo, R. Delisi, M. Pagliaro, Citric acid: emerging applications of key biotechnology industrial product, Chem. Cent. J. 11 (2017) 22.
[37] G. Zhao, Reuse and Recycling of Lithium-Ion Power Batteries, Wiley, New York, 2017.
[38] See Ref. 38, p.404.
[39] China Focus, China Builds Large Power Bank with Retired NEV Batteries, Xinhua, 7 March 2019.
[40] R. Ciriminna, M. Pecoraino, F. Meneguzzo, M. Pagliaro, Reshaping the education of energy managers, Energy Res. Soc. Sci . 21 (2016) 44–48.
[41] R. Ciriminna, F. Meneguzzo, M. Pecoraino, M. Pagliaro, Rethinking solar energy education on the dawn of the solar economy, Renew. Sustain. Energy Rev. 63 (2016) 13–18.
[42] L. Yuanyuan, China's Renewable Energy Installed Capacity Grew 12 Percent across All Sources in 2018, renewableenergyworld.com, 6 March 2019.
[43] Recycle spent batteries, Nat. Energy 4 (2019) 253.
[44] T.P. Narins, The battery business: lithium availability and the growth of the global electric car industry, Extr. Ind. Soc. 4 (2017) 321–328.
[45] R. Ciriminna, L. Albanese, M. Pecoraino, F. Meneguzzo, M. Pagliaro, Solar energy and new energy technologies for mediterranean countries, Global Chall.

LITHIUM

Investing News

Login

# What is Lithium Carbonate?

*Amanda Kay* - *August 15th, 2018*

Lithium production numbers are often broken down in terms of lithium carbonate equivalent. But what is lithium carbonate? Find out here.

**Lithium production is at an all-time high, in part due to the world's efforts to go green via electric vehicles. But what do we know about the different types of lithium?**

Here we discuss lithium carbonate, a lithium compound used in a range of industrial, technical and medical applications.

As Albemarle (NYSE:ALB) notes, lithium carbonate is often "the first chemical in the lithium production chain," with compounds like lithium hydroxide being produced with subsequent steps if needed. For that reason, lithium production numbers are often broken down in terms of lithium carbonate equivalent.



Like other lithium products, lithium carbonate may be produced from brines or from hard-rock deposits. That said, a few companies are also looking to produce the material from clay-based lithium deposits.

Though many companies are interested in producing lithium carbonate, not all investors are familiar with what it is. Here are a few key points on lithium carbonate to keep in mind. Each point is elaborated on further in the article below:

1. Lithium carbonate is used for much more than just lithium-ion batteries.
2. Not all lithium carbonate is created equal.
3. Lithium hydroxide is becoming more popular than lithium carbonate for use in manufacturing lithium-ion batteries.

## 1. Lithium carbonate: Batteries and beyond

Batteries have generated the most excitement in the lithium space over the last few years, with interest spurred by Tesla's (NASDAQ:TSLA) plans to develop lithium-ion battery gigafactories. However, there is more to the lithium market than Tesla, and the market for lithium is not all about batteries.

Looking beyond batteries, lithium carbonate is used in ceramics, glass, cement and aluminum processing. Indeed, while the battery market is certainly growing, the US Geological Survey estimates that glass and ceramics still made up roughly 27 percent of global end-use markets in 2017. Lithium carbonate also has an important use in the pharmaceutical industry: it's been on the World Health Organization's list of essential medicines as a treatment for bipolar disorder.

## 2. Lithium production: Different types of lithium

When it comes to lithium production, not all lithium carbonate is made equal, and end products must meet specific requirements to be used in different applications. For example, battery-grade lithium carbonate can be used to make cathode material for lithium-ion batteries, but most contaminants must be removed in order for the material to be considered battery grade.

Technical-grade lithium carbonate is cheaper than battery-grade material, but such products must have very low concentrations of iron to make the cut for end users. This type of lithium is used in applications for glass and ceramics. It's also worth noting that lithium is used in the form of ore concentrates in industrial applications rather than as lithium carbonate or hydroxide.



## 3. What about hydroxide?

As mentioned, lithium hydroxide is becoming more popular than lithium carbonate, at least in terms of manufacturing electric vehicle batteries. While lithium hydroxide is more expensive, it can also be used to produce cathode material more efficiently, and is actually necessary for some types of cathodes, such as nickel-cobalt-aluminum oxide (NCA) and nickel-manganese-cobalt oxide (NMC).

As Jean Francois Magnan, technical manager for Nemaska Lithium (TSXV:NMX), once explained in an interview, "because hydroxide decomposes at a lower temperature, it accelerates the process. It uses less heat, less energy, so you produce more cathode material with less energy, and you can still use the same equipment."

Demand for lithium production has risen significantly in recent years due to the growing electric vehicle market, and lithium hydroxide is expected to outpace lithium carbonate in terms of demand growth.

That might not sound like good news for lithium carbonate, but as explained above, the material still has plenty of uses beyond batteries. And since it's still a precursor to lithium hydroxide in most cases, lithium carbonate could still have a place in the lithium-ion battery supply chain moving forward.

*This is an updated version of an article originally published by the Investing News Network in 2015.*

*Don't forget to follow us @INN_Resource for more updates!*

**Securities Disclosure: I, Amanda Kay, hold no direct investment interest in any company mentioned in this article.**

**Editorial Disclosure: Nemaska Lithium is a client of the Investing News Network. This article is not paid-for content.**



## GET THE LATEST LITHIUM INVESTING STOCK INFORMATION

Get the latest information about companies associated with Lithium Investing Delivered directly to your inbox.

### LITHIUM INVESTING

Select All Select None

ATTACHMENT 4





Second Use & Long Service Life Holding Back Volume for Recycling 2017-12-04 14:37:51

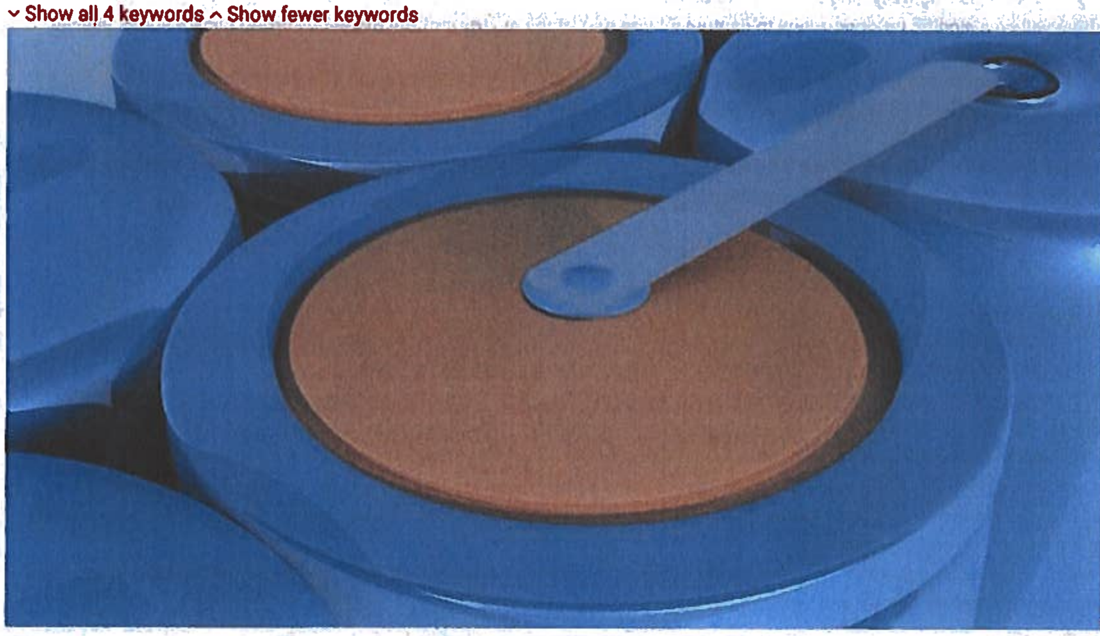
Recycling Could Supply 9% of Global Lithium Demand by 2025

A new analysis of the global lithium-ion end-of-life market has concluded that the total amount of recycled lithium could reach 5800 tonnes (30,000 tonne LCE) in 2025.

From Ben Messenger

lithium-ion batteries Recycling Markets & Policy

Show all 4 keywords ^ Show fewer keywords



LCE = lithium carbonate (Li2CO3) equivalent; determined by multiplying Li value in percent by 5.324 to get an equivalent Li2CO3.

A new analysis from Creation Inn of the global lithium-ion end-of-life market has concluded that the total amount of recycled lithium could reach 5800 tonnes (30,000 tonnes LCE) in 2025, while cobalt is expected to reach 22,500 tonnes.

Long service life, positive prospects for second use and poor collection of portable batteries were said to be the main contributors to the relatively low volume.

More than 66% of the lithium-ion batteries, or 191,000 tonnes, is expected to be recycled in China, feeding the country's fast-growing battery material industry. The%age will be even larger for the important cobalt-containing batteries. 76% of the cobalt in 2025 is expected to be recycled in China without taking production scrap or other sources into account.

The report found excellent prerequisites for a global circular model with batteries moving from first to second use to ultimately be recycled in closed-loop solutions, bringing old material to life in new batteries.

However, for Europe and North America the race for closed-loop solutions can already be lost to China. Large amounts of current end-of-life batteries are exported to China benefiting both the Chinese recycling industry and the domestic producers of battery materials.



When volumes eventually increase in Europe and North America the Chinese recycling industry will have a strong competitive advantage through proven technology and available capacity.

"The limited recycling of lithium-ion batteries in Europe and North America has very little to do with lack of technology but is rather a consequence of a policy framework that doesn't acknowledge the reuse value in the batteries which currently drives them overseas," said Hans Eric Melin, consultant at Creation Inn and author of the study.

"From a circular point of view, it actually works fairly well but it doesn't provide much support to government's ambitions to secure access to critical raw material in EU, US and Canada," he added.

More about this topic

$2000 Fine for Failing to Charge Mandatory 50 cent Bag Charge2019-11-13 15:16:22

Hong Kong Chidren's Wear Shop Fined for Issuing Free Plastic Shopping Bags

Hertfordshire Zoo Keepers Pick Nearly 600 kg of Waste2019-11-08 13:13:07

VIDEO: Paradise Wildlife Park Volunteers Pick Litter Equivalent in Weight to 715 Meerkats

'GAIN' Technology to Enhance Sensor Based Sorting of Wastes2019-11-08 12:08:03

Big Data, AI and Deep Learning – TOMRA Sorting Recycling's Ecomondo Unveil

For the automotive industry there will be a significant opportunity to capture a large part of the energy storage market by taking back electric vehicle batteries and use them in utility-scale storage solutions.

According tot he report the model connects well with similar solutions for vehicle-to-grid in which the vehicle is used as a grid-connected battery, and provides strong growth opportunities while also compensating for revenues that will be lost when sales of spare parts and services are decreasing due to the limited need for maintenance of new electric cars.

The analysis from anticipates that at least 60% of the batteries from electric vehicles will serve in second use solutions before they are sent to recycling.

Other products and services said to have high potential based on the growing lithium-on market are:

Intelligent battery management systems

Flexible and scalable battery pack design

Smart take-back systems

Applications based on second life batteries.

From a raw material perspective recycled battery minerals such as lithium, cobalt, nickel and manganese can be found in new batteries already today. However, the volumes in relation to the rapidly increasing need for materials are still minuscule especially for lithium.

Investments in additional recycling capacity and implementation of new technologies in China, together with the already steep price increase for lithium and cobalt provide important drivers for change. In 2025 the amount of cobalt from recycled batteries is expected to reach almost 20% of the demand. Most of this is expected to be recycled and resynthesized to new cathode material ready to be used in Chinese cathode manufacturer's processes.

The report from Creation Inn is written by Hans Eric Melin who has spent 8 years in the battery recycling industry and more than 15 years in energy and environment-related industries. The study is the result of six months of research based on discussions with industry players, studies of available research and personal experiences from the lithium-ion end-of-life industry.

Besides volume forecasts the report contains overviews of the current end-of-life market, different recycling methods and the emerging second use mark

It also discusses challenges and opportunities for current and new companies in the lithium-ion value chain.

**Read More**

Funding for German Project to Cut the Costs of Lithium-Ion Battery Recycling

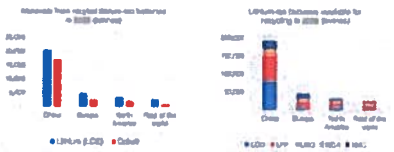
Germany's Federal Ministry of Education and Research has backed a research project aimed ay developing a cost effective means of recycling Lithium-io batteries with the use of electro-hydraulic fragmentation of materials by shock waves.

The Lithium Battery Recycling Challenge

Increasing oil prices, demand for urban vehicles, megacities and focus on sustainable transportation have kickstarted a substantial trend towards automotive electrification such as hybrids and electric vehicles (EVs). Estimates suggest that by 2020, EVs are likely to account for more than 7% of the global transportation market.

Energizer Introduces 'World First' Recycled AA Battery Range

US battery manufacturer Energizer has launched an AA battery range made using 4% recycled material from end-of-life batteries.



© Creation Inn

© Creation Inn

ATTACHMENT 5

NOVEMBER 30, 2017

# Press release: Recycled lithium to reach 9 percent of total lithium battery supply in 2025

## Second use and long service life hold volumes back

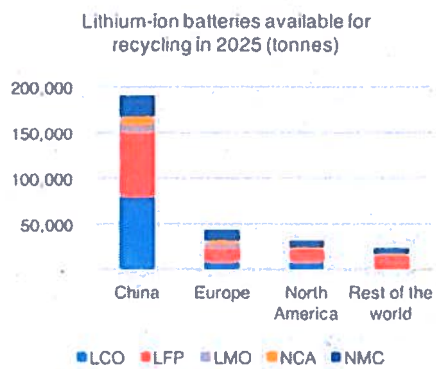
## Europe and North America risk losing recycling industry to China

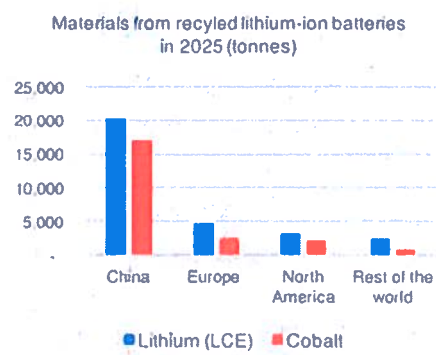
London, November 29, 2017 – **According to a new analysis by Creation Inn of the global lithium-ion end-of-life market, the total amount of recycled lithium can reach 5,800 tonnes (30,000 tonnes LCE) in 2025, while cobalt is expected to reach 22,500 tonnes. Long service life, positive prospects for second use and poor collection of portable batteries are the main contributors to the relatively low volume.**

**More than 66 percent of the lithium-ion batteries, or 191,000 tonnes, is expected to be recycled in China, feeding the country's fast-growing battery material industry. The percentage will be even larger for the important cobalt-containing batteries. 76 percent of the cobalt in 2025 is expected to be recycled in China without taking production scrap or other sources into account.**

In the first analysis of the global end-of-life value chain for lithium-ion batteries Creation Inn finds excellent prerequisites for a global circular model with batteries moving from first to second use to ultimately be recycled in closed-loop solutions, bringing old material to life in new batteries.

However, for Europe and North America the race for closed-loop solutions can already be lost to China. Large amounts of current end-of-life batteries are exported to China benefiting both the Chinese recycling industry and the domestic producers of battery materials. When volumes eventually increase in Europe and North America the Chinese recycling industry will have a strong competitive advantage through proven technology and available capacity.




Hans Eric Melin, consultant at Creation Inn and author of the study says in a comment:

"The limited recycling of lithium-ion batteries in Europe and North America has very little to do with lack of technology but is rather a consequence of a policy framework that doesn't acknowledge the reuse value in the batteries which currently drives them overseas. From a circular point of view, it actually works fairly well but it doesn't provide much support to government's ambitions to secure access to critical raw material in EU, US and Canada."

Better opportunities are given the automotive industry which have an excellent opportunity to capture a substantial part of the energy storage market by taking back electric vehicle batteries and use them in utility-scale storage solutions. The model connects well with similar solutions for vehicle-to-grid in which the vehicle is used as a grid-connected battery, and provides strong growth opportunities while also compensating for revenues that will be lost when sales of spare parts and services are decreasing due to the limited need for maintenance of new electric cars. The analysis from Creation Inn anticipates that at least 60 percent of the batteries from electric vehicles will serve in second use solutions before they are sent to recycling.

Other products and services with high potential based on the growing lithium-on market are:

- Intelligent battery management systems
- Flexible and scalable battery pack design
- Smart take-back systems
- Applications based on second life batteries

From a raw material perspective recycled battery minerals such as lithium, cobalt, nickel and manganese can be found in new batteries already today. However, the volumes in relation to the rapidly increasing need for materials are still minuscule especially for lithium. Investments in additional recycling capacity and implementation of new technologies in China, together with the already steep price increase for lithium and cobalt provide important drivers for change. In 2025 the amount of cobalt from recycled batteries is expected to reach almost 20 percent of the demand. Most of this is expected to be recycled and re-synthesized to new cathode material ready to be used in Chinese cathode manufacturer's processes.

The report from Creation Inn is written by Hans Eric Melin who has spent 8 years in the battery recycling industry and more than 15 years in energy and environment-related industries. The study is the result of six months of research based on discussions with industry players, studies of available research and personal experiences from the lithium-ion end-of-life industry. Besides volume forecasts the report contains overviews of the current end-of-life market, different recycling methods and the emerging second use market. It also discusses challenges and opportunities for current and new companies in the lithium-ion value chain.

**For more information please contact:**

Hans Eric Melin, Managing Director Creation Inn

hanseric@creationinn.com

+44775 692 7479

The report "Circular opportunities in the lithium-ion industry" can be purchased at www.creationinn.com.

TWITTER LINKEDIN 0 LIKES

PREVIOUS

Bloomberg, Charged, Mining.com and many other publications quote Circular Energy Storage's new report

NEXT

Hans Eric Melin invited to speak at University of Oxford

Circular Energy Storage Research and Consulting is part of Creation Inn Ltd

London, N134AH, United Kingdom, +44 775 692 7479

ATTACHMENT 6



ENERGY STORAGE

# It's time to get serious about recycling lithium-ion batteries

## A projected surge in electric-vehicle sales means that researchers must think about conserving natural resources and addressing battery end-of-life issues

*by Mitch Jacoby*

JULY 14, 2019 | APPEARED IN **VOLUME 97, ISSUE 28**

Credit: American Manganese | In a battery-recycling pilot plant near Vancouver, British Columbia, American Manganese engineers examine shredded aluminum recovered from Li-ion battery cathodes.

As the popularity of electric vehicles starts to grow explosively, so does the pile of spent lithium-ion batteries that once powered those cars. Industry analysts predict that by 2020, China alone will generate some 500,000 metric tons of used Li-ion batteries and that by 2030, the worldwide number will hit 2 million metric tons per year.

If current trends for handling these spent batteries hold, most of those batteries may end up in landfills even though Li-ion batteries can be recycled. These popular power packs contain valuable metals and other materials that can be recovered, processed, and reused. But very little recycling goes on today. In Australia, for example, only 2–3% of Li-ion batteries are collected and sent offshore for recycling, according to Naomi J. Boxall, an environmental scientist at Australia's Commonwealth Scientific and Industrial Research Organisation (CSIRO). The recycling rates in the European Union and the US—less than 5%—aren't much higher.

**IN BRIEF**

**Lithium-ion batteries have made portable electronics ubiquitous,** and they are about to do the same for electric vehicles. That success story is setting the world on track to generate a multimillion-metric-ton heap of used Li-ion batteries that could end up in the trash. The batteries are valuable and recyclable, but because of technical, economic, and other factors, less than 5% are recycled today. The enormousness of the impending spent-battery situation is driving researchers to search for cost-effective, environmentally sustainable




**MOST POPULAR IN MATER**

It's time to get serious about recyclin

A surprising portrait of wood's molecı

Why glass recycling in the US is broke

Double diazirine cross-links virtually

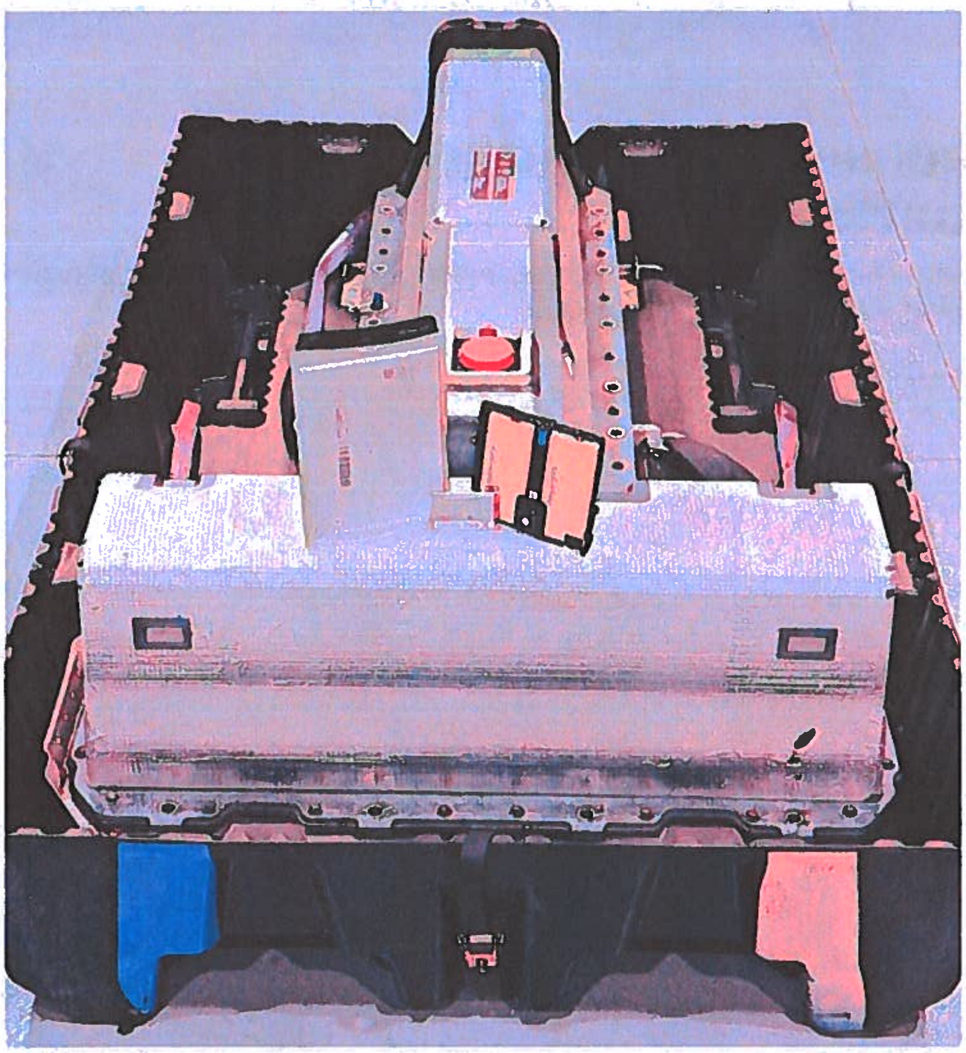
Argon reacts with nickel under pressu

Video: Sunflowers inspire light-trackin

"There are many reasons why Li-ion battery recycling is not yet a universally well-established practice," says Linda L. Gaines of Argonne National Laboratory. A specialist in materials and life-cycle analysis, Gaines says the reasons include technical constraints, economic barriers, logistic issues, and regulatory gaps.

strategies for dealing with the vast stockpile of Li-ion batteries looming on the horizon.

All those issues feed into a classic chicken-and-egg problem. Because the Li-ion battery industry lacks a clear path to large-scale economical recycling, battery researchers and manufacturers have traditionally not focused on improving recyclability. Instead, they have worked to lower costs and increase battery longevity and charge capacity. And because researchers have made only modest progress improving recyclability, relatively few Li-ion batteries end up being recycled.



Credit: Mitch Jacoby/C&EN

The large, inverted, T-shaped object that fills this travel case (black) is an approximately 200 kg Chevy Volt battery pack. Propped on top of it, at left, is a postcard-sized pouch battery, 288 of which make up the Volt's battery pack. For scale, a cell phone battery is shown in the center and an iPad battery at right.

Most of the batteries that do get recycled undergo a high-temperature melting-and-extraction, or smelting, process similar to ones used in the mining industry. Those operations, which are carried out in large commercial facilities—for example, in Asia, Europe, and Canada—are energy intensive. The plants are also costly to build and operate and require sophisticated equipment to treat harmful emissions generated by the smelting process. And despite the high costs, these plants don't recover all valuable battery materials.

Until now, most of the effort to improve Li-ion battery recycling has been concentrated in a relatively small number of academic research groups, generally working independently. But things are starting to change. Driven by the enormous quantity of spent Li-ion batteries expected soon from aging electric vehicles and ubiquitous portable electronics, start-up companies are commercializing new battery-recycling technology. And more scientists have started to study the problem, expanding the pool of graduate students and postdocs newly trained in battery recycling. In addition, some battery, manufacturing, and recycling experts have begun forming large, multifaceted collaborations to tackle the impending problem.

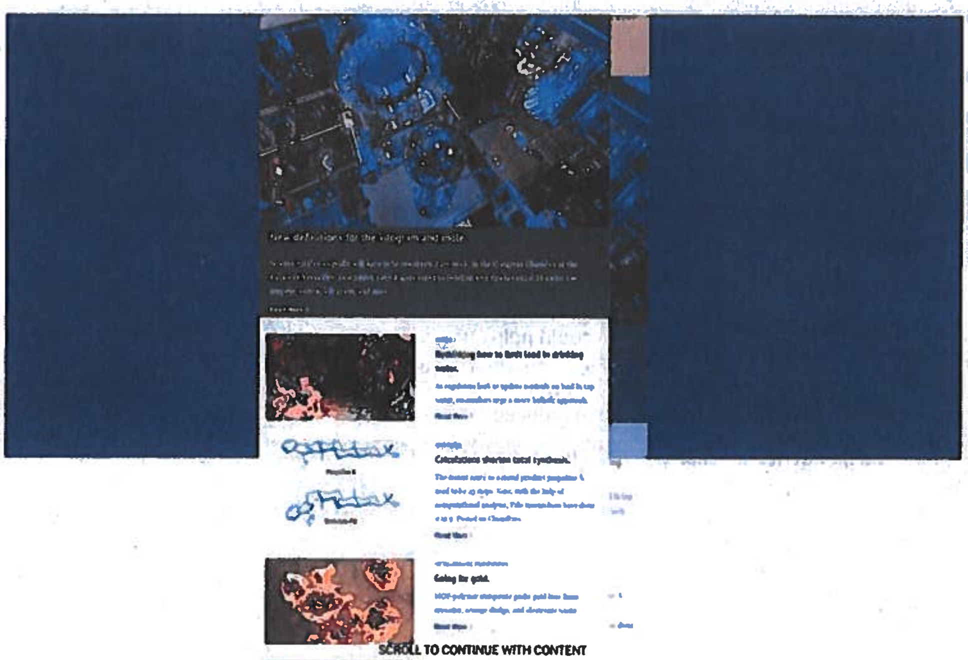


In January, for example, US Department of Energy secretary Rick Perry announced the creation of the DOE's first Li-ion battery recycling R&D center, the ReCell Center. According to Jeffrey S. Spangenberger, the program's director, ReCell's key goals include making Li-ion battery recycling competitive and profitable and using recycling to help reduce US dependence on foreign sources of cobalt and other battery materials. Launched with a $15 million investment and headquartered at Argonne National Laboratory, ReCell includes some 50 researchers based at six national laboratories and universities. The program also includes battery and automotive equipment manufacturers, materials suppliers, and other industry partners.

At the same time, the DOE also launched the $5.5 million Battery Recycling Prize. The program's goal is to encourage entrepreneurs to find innovative solutions for collecting and storing discarded Li-ion batteries and transporting them to recycling centers, which are the first steps in turning old batteries into new ones.

And last year, researchers in the UK formed a large consortium dedicated to improving Li-ion battery recycling, specifically from electric vehicles. Led by the University of Birmingham, the Reuse and Recycling of Lithium Ion Batteries (ReLiB) project brings together some 50 scientists and engineers at eight academic institutions, and it includes 14 industry partners.

**Related: Boosting the performance of aqueous potassium-ion batteries**




## RECYCLING'S BENEFITS

Battery specialists and environmentalists give a long list of reasons to recycle Li-ion batteries. The materials recovered could be used to make new batteries, lowering manufacturing costs. Currently, those materials account for more than half of a battery's cost. The prices of two common cathode metals, **cobalt** and nickel, the most expensive components, have fluctuated substantially in recent years. Current market prices for cobalt and nickel stand at roughly $27,500 per metric ton and $12,600 per metric ton, respectively. In 2018, cobalt's price exceeded $90,000 per metric ton.

In many types of Li-ion batteries, the concentrations of these metals, along with those of lithium and manganese, exceed the concentrations in natural ores, making spent batteries akin to highly enriched ore. If those metals can be recovered from used batteries at a large scale and more economically than from natural ore, the price of batteries and electric vehicles should drop.

In addition to potential economic benefits, recycling could reduce the quantity of material going into landfills. Cobalt, nickel, manganese, and other metals found in batteries can readily leak from the casing of buried batteries and contaminate soil and groundwater, threatening ecosystems and human health, says Zhi Sun, a specialist in pollution control at the Chinese Academy of Sciences. The same is true of the solution of lithium fluoride salts ($LiPF_6$ is common) in organic solvents that are used in a battery's electrolyte.

**BY THE NUMBERS**

**140 million:** The number of electric vehicles predicted to be on the road worldwide by 2030

**11 million:** Metric tons of Li-ion batteries expected to reach the end of their service lives between now and 2030

**30–40%:** The percentage of a Li-ion battery's weight that comes from valuable cathode material

**<5%:** The percentage of Li-ion batteries that are recycled currently

**~100%:** The percentage of the lead in common lead-acid car batteries that gets recycled into new batteries

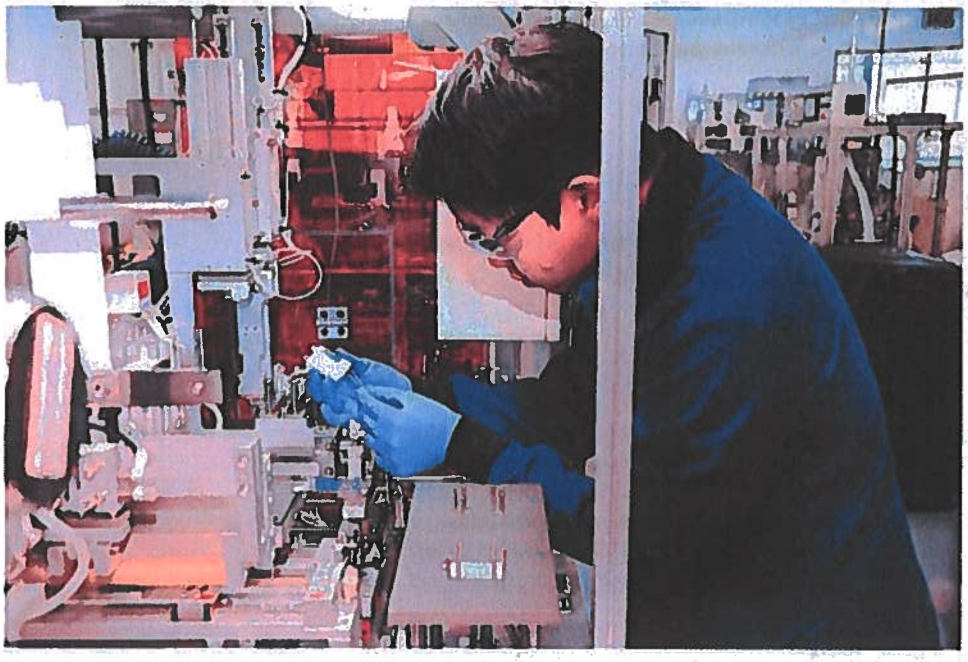
**~$70 billion:** The value of the Li-ion battery market projected for 2022

**Sources:** International Energy Agency, US Department of Energy.

Batteries can have negative environmental effects not just at the end of their lives but also long before they are manufactured. As Argonne's Gaines points out, more recycling means less mining of virgin material and less of the associated environmental harm. For example, mining for some battery metals requires processing metal-sulfide ore, which is energy intensive and emits $SO_x$ that can lead to acid rain.

Less reliance on mining for battery materials could also slow the depletion of these raw materials. Gaines and Argonne coworkers studied this issue using computational methods to model how growing battery production could affect the geological reserves of a number of metals through 2050. Acknowledging that these predictions are "complicated and uncertain," the researchers found that world reserves of lithium and nickel are adequate to sustain rapid growth of battery production. But battery manufacturing could decrease global cobalt reserves by more than 10%.

There are also political costs and downsides that recycling Li-ion batteries could help address. According to **a CSIRO report**, 50% of the world's production of cobalt comes from the Democratic Republic of the Congo and is tied to armed conflict, illegal mining, human rights abuses, and harmful environmental practices. Recycling batteries and formulating cathodes with a reduced concentration of cobalt could help lower the dependence on such problematic foreign sources and raise the security of the supply chain.



Credit: Mitch Jacoby/C&EN
Argonne National Laboratory's Dohyeun Kim prepares pouch-type Li-ion batteries to study battery recycling.

## CHALLENGES IN RECYCLING LI-ION BATTERIES

Just as economic factors can make the case for recycling batteries, they also make the case against it. Large fluctuations in the prices of raw battery materials, for example, cast uncertainty on the economics of recycling. In particular, the recent large drop in cobalt's price raises questions about whether recycling Li-ion batteries or repurposing them is a good business choice compared with manufacturing new batteries with fresh materials. Basically, if the price of cobalt drops, recycled cobalt would struggle to compete with mined cobalt in terms of price, and manufacturers would choose mined material over recycled, forcing recyclers out of business. Another long-term financial concern for companies considering stepping into battery recycling is whether a different type of battery, such as **Li air**, or a different vehicle propulsion system, like **hydrogen-powered fuel cells**, will gain a major foothold on the electric-vehicle market in coming years, lowering the demand for recycling Li-ion batteries.



Battery chemistry also complicates recycling. Since the early 1990s when Sony commercialized Li-ion batteries, researchers have repeatedly tailored the cathode's composition to reduce cost and to enhance charge capacity, longevity, recharge time, and other performance parameters.

Some Li-ion batteries use cathodes made of lithium cobalt oxide (LCO). Others use lithium nickel manganese cobalt oxide (NMC), lithium nickel cobalt aluminum oxide, lithium iron phosphate, or other materials. And the proportions of the components within one type of cathode—for example, NMC—can vary substantially among manufacturers. The upshot is that Li-ion batteries contain "a wide diversity of ever-evolving materials, which makes recycling challenging," says Liang An, a battery-recycling specialist at Hong Kong Polytechnic University. Recyclers may need to sort and separate batteries by composition to meet the specifications of people buying the recycled materials, making the process more complicated and raising costs.

Battery structure further complicates recycling efforts. Li-ion batteries are compact, complex devices, come in a variety of sizes and shapes, and are not designed to be disassembled. Each cell contains a cathode, anode, separator, and electrolyte.



Cathodes generally consist of an electrochemically active powder (LCO, NMC, etc.) mixed with carbon black and glued to an aluminum-foil current collector with a polymeric compound such as poly(vinylidene fluoride) (PVDF). Anodes usually contain graphite, PVDF, and copper foil. Separators, which insulate the electrodes to prevent short circuiting, are thin, porous plastic films, often polyethylene or polypropylene. The electrolyte is typically a solution of $LiPF_6$ dissolved in a mixture of ethylene carbonate and dimethyl carbonate. The components are tightly wound or stacked and packed securely in a plastic or aluminum case.

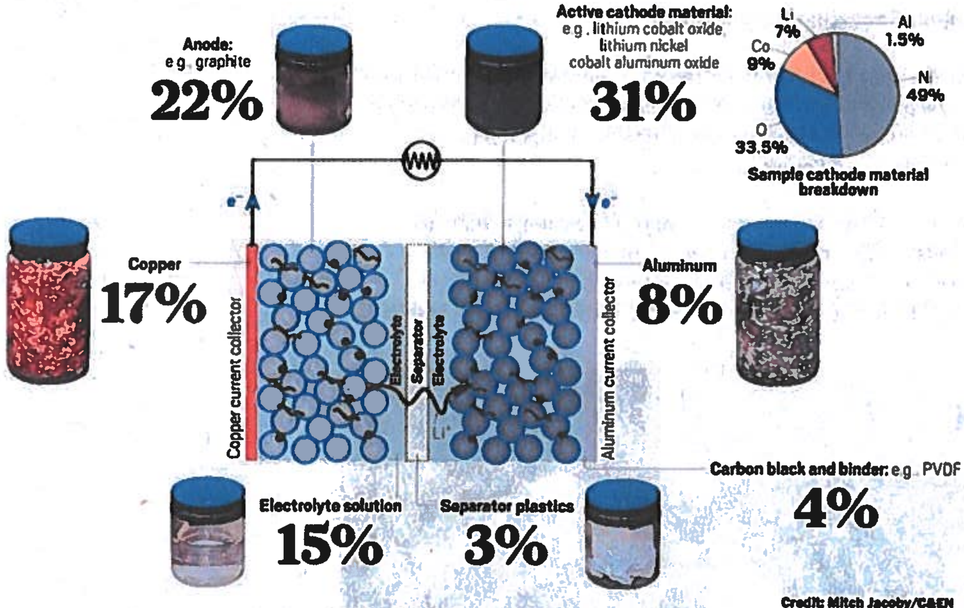
**Related: Matthey advances lithium nickel oxide battery material**

Large battery packs that power electric vehicles may contain several thousand cells grouped in modules. The packs also include sensors, safety devices, and circuitry that controls battery operation, all of which add yet another layer of complexity and additional costs to dismantling and recycling.

All these battery components and materials need to be dealt with by a recycler to get at the valuable metals and other materials. In stark contrast, lead-acid car batteries are easily disassembled, and the lead, which accounts for about 60% of a battery's weight, can be separated quickly from the other components. As a result, **nearly 100% of the lead** in these batteries is recycled in the US, far surpassing **recycling rates for glass**, paper, and other materials.

## Inside a Li-ion battery

All the components of a Li-ion battery have value and can be recovered and reused. Currently, most recyclers recover just the metals. The pie chart describes a cathode material known as NCA, which is made of lithium nickel cobalt aluminum oxide.




Source: Argonne National Laboratory.

## IMPROVING RECYCLING METHODS

Several large pyrometallurgy, or smelting, facilities recycle Li-ion batteries today. These units, which often run near 1,500 °C, recover cobalt, nickel, and copper but not lithium, aluminum, or any organic compounds, which get burned. The facilities are capital intensive, in part because of the need to treat the emission of toxic fluorine compounds released during smelting.

Hydrometallurgy processing, or chemical leaching, which is practiced commercially in China, for example, offers a less energy-intensive alternative and lower capital costs. These processes for extracting and separating cathode metals generally run below 100 °C and can recover lithium and copper in addition to the other transition metals. One downside of traditional leaching methods is the need for caustic reagents such as hydrochloric, nitric, and sulfuric acids and hydrogen peroxide.

Researchers running bench-scale studies have identified potential improvements to these recycling methods, but only a handful of companies run recycling tests on the methods at the pilot-plant scale. In the Vancouver, British Columbia, area, an American Manganese facility converts 1 kg/h of cathode scrap to a precursor that manufacturers can use to synthesize fresh cathode material. Scrap refers to off-spec cathode powder, trimmings, and other waste collected from battery manufacturing.



Zarko Meseldzija, the company's chief technical officer, describes the scrap as "low-hanging fruit," a convenient material to use for experiments before boosting the scale of operations and moving on to actual spent batteries. He explains that the company's process relies on sulfur dioxide for leaching cathode metals and does not use hydrochloric acid or hydrogen peroxide.

Battery Resourcers in Worcester, Massachusetts, runs a pilot plant that processes Li-ion batteries at a rate of up to roughly 0.5 metric tons per day and is actively working to increase capacity by a factor of 10, according to CEO

Eric Gratz. Many current recycling methods yield multiple single-metal compounds that must be combined to make new cathode material. Battery Resourcers' process precipitates a mixture of nickel, manganese, and cobalt hydroxides. This mixed-metal cathode precursor simplifies battery preparation and could lower manufacturing costs.

**Related: Recycling renewables**

Meanwhile, the DOE's ReCell team is pursuing so-called direct recycling methods for recovering and reusing battery materials without costly processing. One approach calls for removing the electrolyte with supercritical carbon dioxide, then crushing the cell and separating the components physically—for example, on the basis of density differences.

In principle, nearly all the components can be reused after this simple processing. In particular, because the method does not use acids or other harsh reagents, the morphology and crystal structure of the cathode materials remain intact, and the materials retain the electrochemical properties that make them valuable. Gaines says more work is needed to implement this cost-saving approach.


Credit: Alireza Rastegarpanah and Rustam Stolkin/Extreme Robotics Lab

At the University of Birmingham, ReLib team member Alireza Rastegarpanah develops robotic methods for safe, automated processing of spent Li-ion batteries.

At the University of Birmingham's ReLiB project, principal investigator Paul Anderson says the team sees a clear opportunity to boost the economic efficiency of battery recycling through automation. To that end, the team is developing robotic procedures for sorting, disassembling, and recovering valuable materials from Li-ion batteries. Birmingham's Allan Walton, a coinvestigator, adds that using robotic devices to disassemble batteries could eliminate human workers' risk of electrical and chemical injury. Automation could also lead to enhanced separation of battery components, increasing their purity and value, he says.

Although most of these strategies remain at an early stage of development, the need for them is growing. Currently, the number of end-of-life electric-vehicle batteries is low, but it's about to skyrocket. Numerous impediments stand in the way of large-scale recycling, but "opportunities always coexist with challenges," says An of Hong Kong Polytechnic. It's time to take the bull by the horns and get serious about recycling Li-ion batteries.

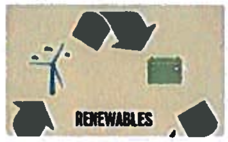
Chemical & Engineering News
ISSN 0009-2347

## YOU MIGHT ALSO LIKE...

**Boosting the performance of aqueous potassium-ion batteries**

SPECIALTY CHEMICALS

**Matthey advances lithium nickel oxide battery material**




**Recycling renewables**

**LC-MS/MS Analysis of PFAS**
by Shimadzu Corp.

## COMMENTS

**TITO CALOI**
(November 6, 2019 3:47 PM)
It'ld be better to recover the battery instead of recover the materials there is inside.
**Reply »**

## LEAVE A COMMENT

Name

Email*

Comments by first-time contributors will be reviewed prior to appearing on the site. This review is done by humans and not always immediately. You may be laudatory or critical, but please stay on topic and be respectful of the author and your fellow readers. We reserve the right to remove any comments that are profane, obscene, abusive, or otherwise inappropriate. Email addresses are required so that we can verify you are not a robot overlord and in case we need to contact you about your comment privately. They will not appear on the site.

Submit

*Required to comment

ATTACHMENT 7



# Avoid the Spark Campaign Continues Battery Safety Awareness in the Bay Area

Local events to spotlight 'hidden dangers' of trashed batteries while supporting California Fire Foundation

**SAN FRANCISCO — October 4, 2018 —** This month, the ***Avoid the Spark***™ campaign – a public education effort to reduce battery safety incidents – returns to the Bay Area to engage the community. Efforts include local county battery collections, a cornerstone event benefiting California Fire Foundation, and the launch of a dedicated battery safety resource webpage, www.avoidthespark.com. This second phase builds on the ***Avoid the Spark*** campaign launch in May, spurred by the growing epidemic of battery-related fires at recycling and waste facilities along with the 'hidden dangers' of trashing lithium-based batteries.

Coordinated by Call2Recycle®, the country's first and largest consumer battery recycling program, and supported by industry leaders and Bay Area municipal county partners, the campaign educates on the proper handling and disposal of old batteries to prevent fires, protecting people and property.

A recent California Product Stewardship Council survey reported that of 26 surveyed waste facilities from all over California, 83 percent had a fire at their facility. Sixty-five percent of the reported fires were due to batteries. While the Call2Recycle program is seeing a decrease of batteries without terminal protection received from the Bay Area, there remains a gap between consumer knowledge and practice of battery safety.

"This spring, we launched the first phase of ***Avoid the Spark*** in the Bay Area, but we know that there is still much work to do in raising awareness about safely handling, transporting and disposing of batteries," said Carl Smith, CEO and president of Call2Recycle, Inc. "Through these partnerships, events and educational resources, our goal is to shift consumer behavior away from trashing batteries and to recycle them as a critical part of our environmental mission."

The cornerstone ***Avoid the Spark*** battery collection event will take place in San Francisco on Friday, October 26th from 11:00 a.m. to 3:00 p.m. at Spark Social SF, located at 601 Mission Bay Boulevard in North San Francisco, complete with giveaways and informational resources. The community is invited to bring their old household batteries to be recycled and for every pound of batteries received, the campaign will donate to California Fire Foundation, a nonprofit providing emotional and financial assistance to families of fallen firefighters, as well as firefighters and the communities they protect.

For more information, visit www.avoidthespark.com

**About Call2Recycle, Inc.**

Call2Recycle, Inc., is committed to protecting and preserving the environment through collecting and recycling consumer batteries and cellphones. Founded in 1994, the not-for-profit organization works on behalf of stakeholders to provide its battery recycling program to consumers across the U.S. Visit call2recycle.org. Follow on Facebook, Twitter or LinkedIn.

## Find a Drop-off Location

Enter Postal Code


## Explore the Secret Life of Batteries

Batteries power many of our devices, but what happens when they lose their charge?

## Sustainability Stories:

In the 25 years we have been operating our recycling program, we have worked with various companies and municipalities that share our core value to do the right thing for the environment. Check out what some of these organizations have to say about the Call2Recycle program.
Read more

## Contact Us

**Hours of Operation:**

M – F : 8:00am – 6pm (EST)
S/Su : CLOSED

For more information, please contact:

Company Contact

Dori Mendel
678-218-1084
dmendel@call2recycle.org

Media Contact

SRPR for Call2Recycle
Brenda Patterson
440-623-9581
brenda@shevrushpr.com

**Contact Information:**

Phone: 1-877-723-1297
Contact us

RELATED POSTS

- No related posts found