LITHIUM BATTERY RECYCLING R&D CENTER (RECELL)

Advantages of Lithium Battery Recycling

Currently, lithium-ion batteries contain a substantial amount of cobalt, a critical material that is both expensive (in 2017, average annual cobalt prices more than doubled) and dependent on foreign sources for production.1 The Democratic Republic of Congo supplies nearly 60% of the world's cobalt with 60% going to China. China is the world's leading producer of refined cobalt and a leading supplier of cobalt imports to the United States[1]; this dependency could become a concern for U.S. end-users. The growth in demand for lithium-ion batteries for EVs will establish EVs as the largest end-user of cobalt and lithium and could potentially create a cobalt and lithium supply risk.[2][3][4]

In addition to addressing supply security issues with cobalt, there are substantial environmental benefits to recycling because of resource preservation itself. When key battery materials (e.g., cobalt or lithium) are derived from natural resources as compared to from spent batteries, the environmental footprint is a lot larger (see Figure 1) and therefore less benign. The benefits of recycling lithium-ion batteries are considerable, both from an economic and a national security perspective.

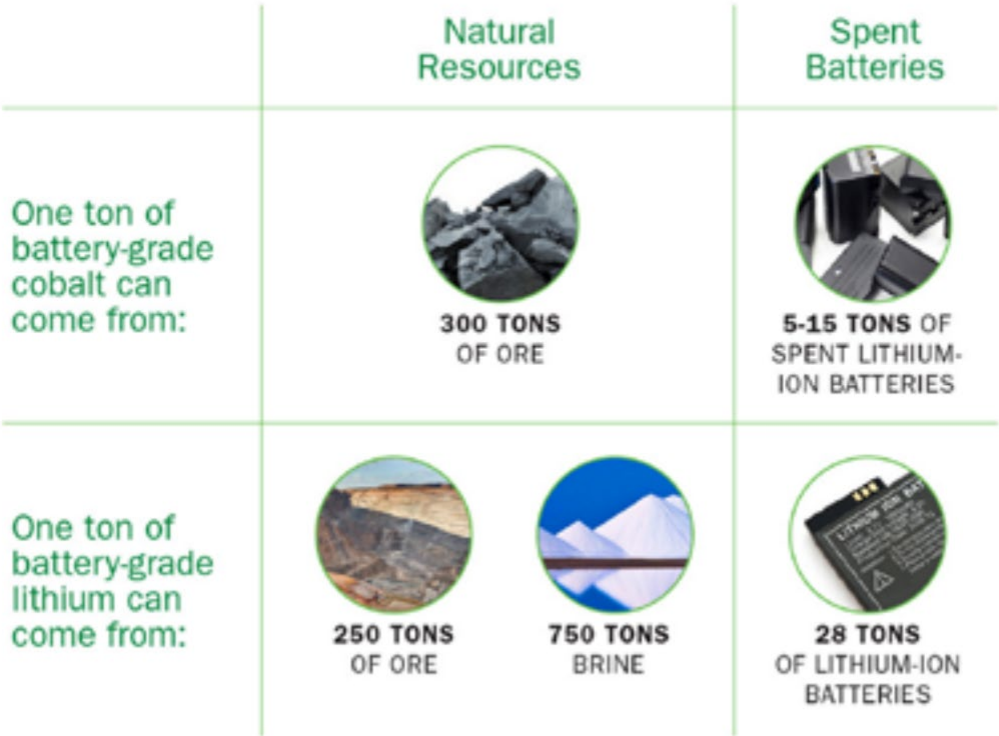

Figure 1 Potential Material Supply from Recycled Li-Ion Batteries Source: Argonne National Laboratory

Lithium Battery Recycling Challenges

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[1] M. Mann, A. Mayyas, D. Steward, Impact of Li-Ion Recycling on the Supply Chain, NREL, presented at the International Li-Ion Battery Recycling Work

[2] Hype Meets Reality as Electric Car Dreams Run Into Metal Crunch, Bloomberg, January 2018, https://www.bloomberg. com/graphics/2018-cobaltbatteries/?cmpId=flipboard

[3] Lithium-Ion Batteries: Examining Material Demand and Recycling Issues, L. Gaines and P. Nelson, TMS 2010 Annual Meeting and Exhibition, Seattle, WA (February 2010)

[4] National Renewable Energy Laboratory analysis, utilizing data published by Bloomberg New Energy Finance, 2018, https://www.bloomberg.com/ news/articles/2018-06-10/ cobalt-battery-boom-waversas-china-demand-lull-bringsout-bears.

As the United States tries to reduce its dependence on foreign sources for batteries and raw materials for their construction, and to diminish environmental impact of spent batteries, scientists and industry leaders are looking for new ways to recycle and recover lithium-ion battery components. More than 15 cathode chemistries are used in lithium-ion batteries that make them practical for more applications and therefore increases demand for materials. As new chemistries become commercially available, the need arises to develop flexible and reliable processes to maximise economic value to the recycler. Advanced recycling approaches can significantly meet the demand for materials.

Battery recycling and sustainability projects investigate the material and energy flows pertaining to battery material production, battery manufacturing and assembly, and battery recycling, to characterise the life-cycle energy and environmental burdens of lithium-ion batteries (LIBs). By interacting with battery manufacturers and recyclers, researchers obtain primary data on the energy and water use for commercialised LIB production and recycling, and identify environmental impact drivers, production bottlenecks, and other barriers, for LIB production and recycling. Challenges to be faced for Li-ion battery recycling are shown in Table 1, along with suggested R&D areas for addressing them. Detailed understanding of recycling processes will be necessary to maximise material recovery.

Challenge	R&D Needed to Address
Long-term performance of some recycled materials is not proven	Long-term testing
There is no standard chemistry or design	Convergence of chemistries and designs, Flexible processes, Design for recycling Automation
There are no regulations, so restrictive ones could be imposed	Fashioning regulations that will protect health and safety without hindering recycling
Many of the constituents have low market value	Process development to recover multiple high-value materials
Low value of mixed streams, prevention of fires and explosions	Effective labeling and sorting

Table 1 Challenges for Li-Ion Battery Recycling

ReCell Center officially launched

The U.S. Department of Energy (DOE) Vehicle Technologies Office (VTO) invests in early-stage research to develop recycling technologies for extraction and reuse of the main components and materials in lithium-ion batteries that would be economical and have lower energy and environmental impacts. As part of this effort, it has launched the ReCell Battery Recycling R&D Center, a $4M/ year effort involving a multiple-lab consortium (in addition to Argonne, ReCell includes Oak Ridge National Laboratory and the National Renewable Energy Laboratory, as well as Worcester Polytechnic Institute, Michigan Technological University, and University of California-San Diego) which focuses on novel approaches to recycling in order to maximise economic yield of batteries at their end of life. Current lithium-ion recycling methods, such as hydrometallurgical and pyrometallurgical processes, only enable the recovery of specific metals, and in a form that is of low-value to battery manufacturers (See Figure 2). To make lithium-ion recycling profitable, without large service fees, and to encourage its growth as an industry, methods of direct recycling need to be developed. The focus areas of the ReCell Center therefore include direct recovery of cathode material, separation methods, battery design for recycling, recovery of other materials, and advanced characterization of recycled material. The ReCell Centre was officially launched on January 17, 2019.[5]

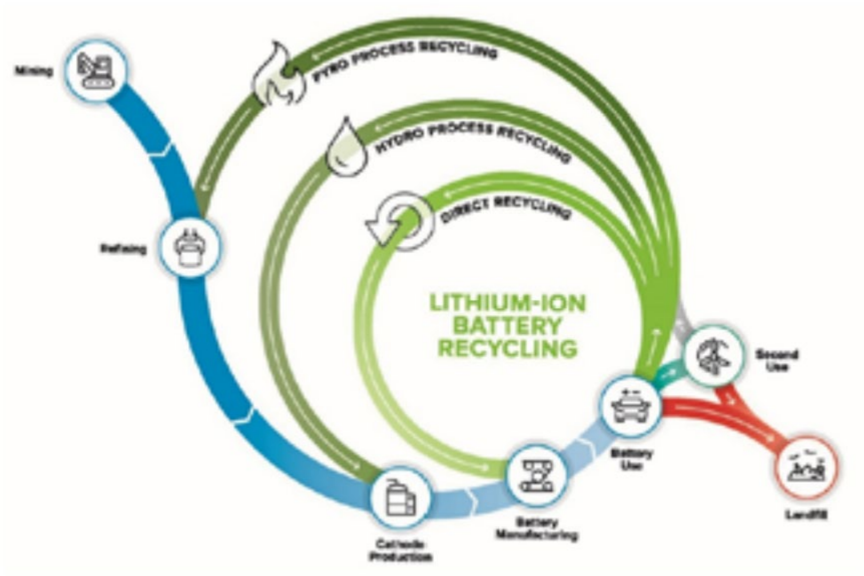

Figure 2 Direct recycling recovers cathode material instead of metal salts, offering the most potential for cost effectiveness. Source: Argonne National Laboratory

Industry Collaboration Meeting

A ReCell Industry Collaboration Meeting was held Nov. 7-8, 2019 at the Argonne National Laboratory, where representatives from industry, government, and academia discussed innovative approaches for lithium-ion battery recycling. David Howell, Deputy Director of DOE's Energy Efficiency and Renewable Energy's Vehicle Technologies Office (VTO) gave the keynote talk at the event.

The meeting drew representatives from a wide range of companies that focus on different parts of the battery life cycle. Attendees from automotive original equipment manufacturers (OEM) for instance, are not directly involved in the recycling process but need to make sure that there are available pathways for their batteries to be recycled. Other attendees represented battery recycling start-ups, materials suppliers, battery manufacturers, etc.

Electric car owners are unable to simply recycle their batteries at the end of the vehicle's lifetime; they must pay for a service if they choose to do so. The potential of direct recycling technology, which seeks to convert spent batteries to highervalue products as opposed to the current products of lesser value, could offer a more cost-effective way to reuse batteries than today's methods.

[5] https://www.energy.gov/ articles/energy-departmentannounces-battery-recyclingprize-and-battery-recycling-rdcenter

Argonne is demonstrating these new direct recycling technologies to determine if the techniques could be viable on industrial scale.

The ReCell Industry Collaboration Meeting also addressed ways to derive more value from recycling electrolyte and foil materials as well as improvements that could be made in supply chain analysis. Although most of the cost savings for battery recycling would come from a move to direct recycling, these additional areas of research could provide other benefits that would make battery recycling more attractive as a whole.

LITHIUM BATTERY RECYCLING PRIZE

Lithium Battery Recycling Prize Established

To address the lack of a well distributed, efficient, and profitable infrastructure to enable recycling of lithium-ion batteries, VTO has established a Battery Recycling Prize (amounting to $5.5-million) to incentivise American entrepreneurs to find innovative solutions to solve current challenges associated with collecting, storing, and transporting spent or discarded lithium-ion batteries for eventual recycling. The goal of the Battery Recycling Prize is to develop innovative business and technology strategies with the potential to capture 90% of all lithium-based battery technologies (consumer electronics, stationary, and transportation applications) in the United States; and that make collecting, sorting, storing, and transporting lithium-based batteries safe, efficient, and profitable. The prize will facilitate entrepreneurs to leverage the resources of incubators, universities, and the national labs to transform innovative early-stage concepts into prototypes primed for industry adoption. Successful concepts must consider cost-effective methods or technologies such as separation and sorting of various collected battery types and sizes; rendering lithium-based batteries safe or inert during storage; or reducing the hazardous classification of lithium-based batteries in order to reduce shipping costs.

The three consecutive innovation phases of the Battery Recycling Prize (see Figure 3) will accelerate entrepreneurs' efforts to create disruptive solutions to collect, store, and transport 90% of spent or discarded lithium-ion batteries. In each phase, the winners are determined by a panel of expert judges evaluating concepts based on feasibility, cost to implement, and potential impact.

Figure 3 The areas of interest for the Lithium-ion Battery Recycling Prize.[6]

Lithium Battery Recycling Prize Phase I Winners Declared

[6] Energy Storage Division, Transportation Research, National Renewable Energy Laboratory (NREL), Golden, CO, 80401, USA

NREL was selected as the Battery Recycling Prize administrator to support DOE with implementation and execution of the prize elements. Over 50 submissions were received for Phase I of the Prize. After review from industry experts and the Federal Consensus Panel, DOE determined that 15 of the submissions (see Table 2) adequately met the criteria for innovativeness, impact, feasibility, and technical approach outlined in the Prize Rules.[7] Assistant Secretary Daniel Simmons presented the winner announcement at NREL on September 25, 2019.[8]

Winner	Project Title
Admiral Instruments	Battery Sorting with Voltammetry and Impedance Data
EEDD	Battery Self-Cooling for Safe Recycling
Holman Parts Distribution	Holman Parts Reverse Logistics Recycling Solution
Li Industries	Smart Battery Sorting System
LIBIoT	Innovative Battery Collection System by Lithium-Ion Battery Internet-of-Things (LIBIoT)
OnTo Technology	Li-Ion Identification
Powering the Future	Banking Today's Materials to Power Tomorrow
Renewance	Reverse Logistics Marketplace
Smartville	Distributed Battery Conditioning HUB
SNT Laser Focused	Utilizing Laser Cutting for Efficient Battery Pack Dismantling
Store Packs Umicore	Development of Four U.S. Collection and Storage Sites for Lithium-Ion Automotive Battery Packs
Team EVBs	A Circular Economy for Electric Vehicle Batteries
Team Portables	Reward to Recycle – Closing the Loop on Portables
Team RRCO	Composite Discharge Media
Titan AES	IonView-Ultrasonic LIB Automated State of Health (SoH) 1 Second Test

Table 2 Lithium-ion battery recycling prize Phase I contest winners

US-GERMANY COLLABORATION ON BATTERY INTERFACES

On March 26th and 27th 2018, leading battery researchers from the United States and Germany met at the Argonne site office in Washington DC for a day and a half meeting to discuss the latest developments in the area of battery interfaces, the challenges, and the research needs to dramatically improving the understanding of electrochemical interfaces. The discussions were focused around next-generation battery chemistries, with emphasis on Li-metal as an anode material. Li-metal based batteries are a key enabler for ushering in a new era of battery development leapfrogging the presently used Li-ion batteries and enabling low cost, long range EV's.

[7] https:// americanmadechallenges.org/ batteryrecycling

[8] https://www.energy.gov/eere/ articles/energy-departmentannounces-phase-1-winnersbattery-recycling-prize

Here, interfaces play a crucial role in dictating the performance of the battery: interfaces are responsible for battery degradation, their resistance dictates the power capability, and reactions at the interface are known to lead to safety issues. Understanding the interface and designing methods to control reactivity remains a crucial need for developing better batteries.

The workshop presentations focused on describing the state of the knowledge in liquid electrolytes, polymer electrolytes and hard solid ceramic and glass electrolyte systems. Presentations related to mathematical model across length scales, from the atomistic to the continuum-scale described what can be predicted today and the needs for the future. The future needs in characterisation techniques needed to probe the interface under in situ operando conditions were also discussed. The workshop showed that while a lot is known about the interface, there is a need for more sophisticated tools and techniques in order to explore this rich research topic. Moreover, it was clear that there was synergistic research expertise in the two countries and that a close collaboration between the research can result in the total being a sum of the parts. The workshop resulted in the identification of key areas of study related to interfaces in next-generation Li-metal based battery chemistries (see Table 3).

Area	Topics
Li metal/liquid electrolyte interface	Understand reactivity and formation of SEI layers in Li and its changes with time.
	Role of the electrolyte composition on reactivity and dendrite formation.
	Experimental and modeling tools that can track dynamics changes at the interface.
Li metal/solid (polymer, ceramic) electrolyte interface	Role of grains and grain boundaries on charge transport and transfer
	Clarify the role of SEI on the evolution of the interface in polymer and ceramics.
	Determine the mechanical properties of the interface layers (Li, polymer, ceramic), and changes during cycling
Cathode/solid (polymer, ceramic) electrolyte interface	Determine the impact of electro-chemo-mechanical changes at the solid-solid interface
	Determine the mechanism of transport and the role of interface coherence on performance.
	Develop tools to probe the buried interface including visualization methods, electrochemistry, and theory across length scales.

Table 3 Key areas of study for interfaces in next generation Li-metal based battery chemistries

Following the workshop, discussions continued between researchers from the two countries. The group reassembled on 14th-15th November, 2018 in Munster, Germany to firm up the details of the collaboration and determine goals and milestones for specific research topics. In addition, plans were drawn to strengthen the collaboration via short-term (<1 month) exchange of personnel and of samples. A summer school was planned to disseminate the knowledge gained from the research to students and early-career researchers from the two countries. A formal kick-off meeting took place on 10th -11th July, 2019, at the Argonne National Laboratory.

NOBEL PRIZES IN CHEMISTRY AWARDED TO BATTERY RESEARCHERS

On the 9th October, 2019, the Royal Swedish Academy of Sciences awarded the 2019 Nobel Prize in Chemistry to three scientists who developed lithium-ion batteries. The scientists include Prof. John B. Goodenough at the University of Texas at Austin, Prof. M. Stanley Whittingham at Binghamton University and Prof. Akira Yoshino at the Meijo University in Nagoya, Japan. VTO has partially funded the R&D for the first two researchers (see Figure 4) over the long term. The U.S. DOE Secretary of Energy congratulated the researchers in a statement issued by DOE. Descriptions of their VTO-supported projects have been regularly included in all VTO Batteries R&D annual progress reports over the past 20-plus years.

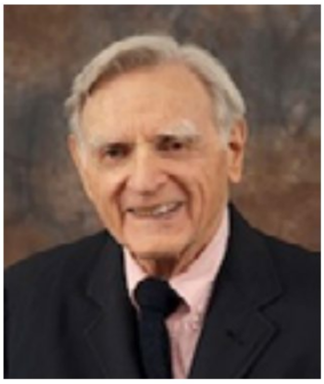


Figure 4 2019 Nobel Laureate battery researchers partially funded by VTO Left: John B. Goodenough, University of Texas, Austin Right: Stanley Whittingham, Binghamton University

NEXT STEPS

The OA, in conjunction with other colleagues in the field, is planning the next discussion meeting. The schedule for this meeting is not yet decided. The OA is working with representatives from the member countries to identify topics and locations for future meetings.