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

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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]

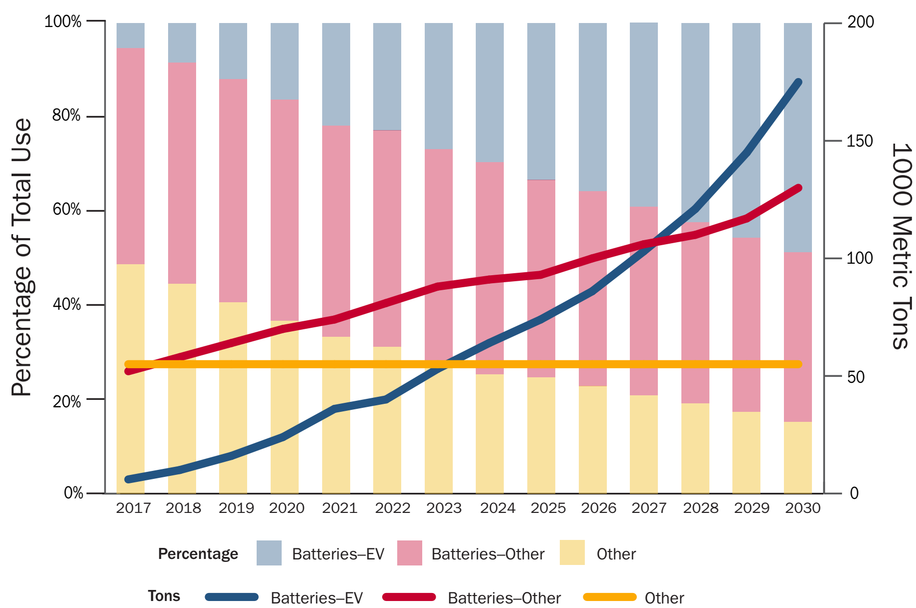
Demand for global production of battery materials, such as lithium, cobalt, manganese, nickel, and graphite, will grow at similar rates. In fact, the growth in demand for lithium-ion batteries for EVs will establish EVs as the largest end-user of cobalt and lithium, and could create a particularly high 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/

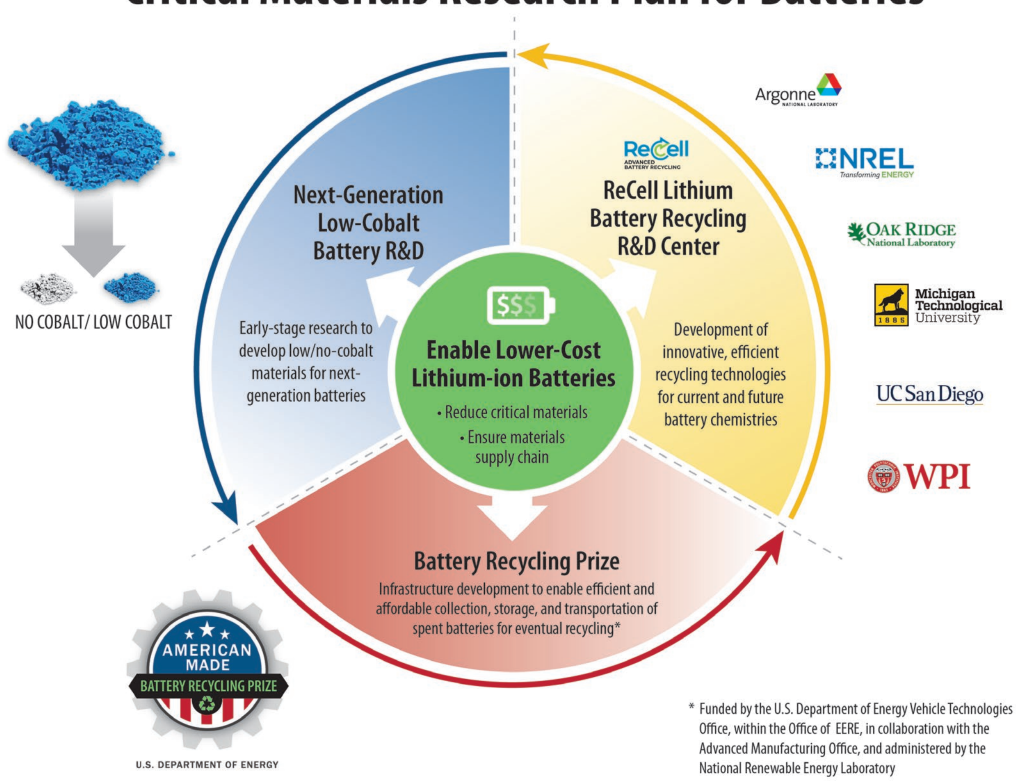
To mitigate potential lithium-ion battery critical materials supply risks, DOE has established the following goal:

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



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

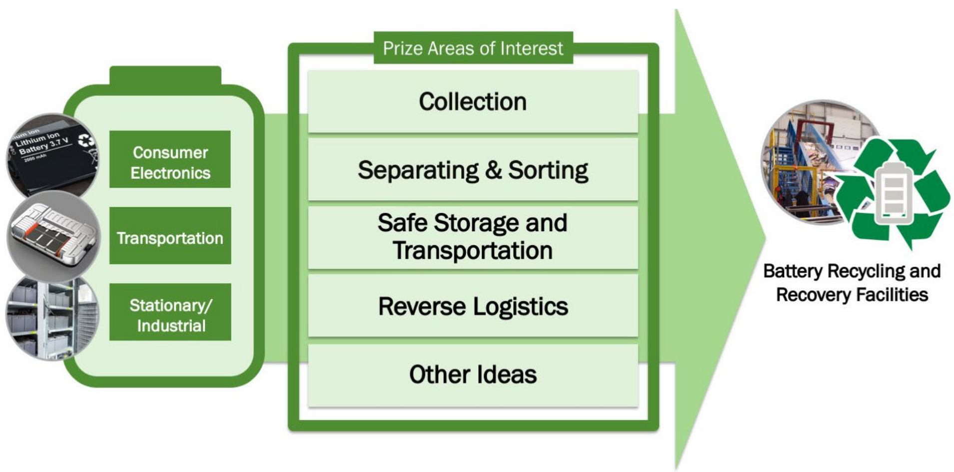
Accelerated efforts to create cost-effective, disruptive solutions to collect, sort, store, and transport 90% of spent or discarded lithium-ion batteries for eventual recycling.

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.

	Natural Resources		Spent Batteries
One ton of battery-grade cobalt can come from:	**300 TONS** OF ORE		**5-15 TONS** OF SPENT LITHIUM-ION BATTERIES
One ton of battery-grade lithium can come from:	**250 TONS** OF ORE	**750 TONS** BRINE	**28 TONS** OF LITHIUM-ION BATTERIES

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

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Photos on page 7 from iStock:
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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.

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