U.S. Department of Energy
Advanced Research Projects Agency – Energy (ARPA-E)

Request for Information (RFI)
DE-FOA-0003027
on
Achieving Circularity of the Domestic Battery Supply Chain

Introduction

The purpose of this RFI is to solicit input for a potential future ARPA-E research program focused on achieving a circular and domestic battery supply chain for various types of electric vehicles including scooters, cars, buses, trucks, trains, ships, and aircrafts. A circular battery supply chain keeps materials and products in circulation at their highest level of performance for as long possible. It is based on a system-level approach that minimize material use, waste, and emissions through the selection of regenerative materials and sustainable designs and manufacturing processes of parts and products. From an economic standpoint, it aims to manage supply chain risks and recover lost manufacturing value.

The potential program is not concerned with supplies of critical minerals or with existing battery recycling processes. Instead, it focuses on alternative strategies that can be implemented to achieve circularity including servicing, upgrading, refurbishing, and remanufacturing of batteries. The primary goals are (1) to identify materials (e.g., electrode materials, electrolytes, adhesives) amenable to in-cell regeneration to prolong the life of batteries, (2) to develop sustainable design and manufacturing of battery cells, modules, and packs that facilitate serviceability, disassembly, refurbishing, and recovery of materials and/or components at the end of life, and (3) to minimize waste, energy consumption, and greenhouse gas emissions during the battery lifecycle. Such transformation should be achieved without affecting the performance and safety of the battery packs. ARPA-E is seeking information at this time regarding transformative and implementable technologies that can:

(a) Extend the life of battery materials, cells, modules, and/or pack through regeneration, servicing or maintenance, reuse, refurbishment, and remanufacturing. Examples include selection of electrode materials that can be regenerated through thermomechanical, chemical, and/or electrochemical treatments,
(b) Develop designs and manufacturing processes for cells, modules and packs that can be easily disassembled to enable servicing, reuse, refurbishing, or remanufacturing, and
(c) Minimize the overall amount of waste generated, energy consumed, and greenhouse gas emitted throughout the battery manufacturing, servicing, and recycling processes. Examples include designs that avoid permanent bonding or any fabrication that requires destructive disassembly (e.g., shredding).

Background

The electrification of all forms of vehicles promises to decarbonize the transportation sector which accounted for 27% of the total U.S. greenhouse gas emissions in 2020.[1] The demand for electrical energy storage devices in general, and lithium-ion batteries (LIBs) in particular, to power electric vehicles (EVs)

[1] Fast Facts U.S. Transportation Sector Greenhouse Gas Emissions 1990 –2020, Office of Transportation and Air Quality EPA-420-F-22-018, May 2022.

is expected to surge dramatically in the coming decades fueled by consumer demand for cleaner vehicles, higher cost of gasoline, and legislations banning the sales of internal combustion engine vehicles. The life expectancy of LIBs for EVs ranges between 10 and 15 years depending on the intensity and conditions of use. Therefore, the volume of spent batteries is also expected to rise dramatically albeit with a time lag.

Battery material selection and design has so far focused on performance as well as efficient and cost-effective manufacturability. Unfortunately, little consideration has been given to their end of life. Battery Original Equipment Manufacturers (OEMs) are under economic pressure to produce large volumes of LIBs at the lowest cost. The current price of EV batteries was around $150/kWh in 2022 and is projected to reach about $80/kWh by 2030.[2] However, the supply of minerals such as cobalt, nickel, and lithium is limited and insufficient to meet the expected demand.[3] The price of these minerals has featured strong temporal fluctuations in recent years and an overall upward trend. This has led the industry to reduce the amount of cobalt in the material chemistry of lithium nickel manganese cobalt oxide $LiNi_xMn_yCo_zO_2$ (or NMC) batteries from NMC 111 (33% Ni, 33% Mn, 33% Co) to NMC 811 (80% Ni, 10% Mn, 10% Co). Further cost reduction has been achieved with lithium iron phosphate $LiFePO_4$ (LFP) batteries whose market share has been steadily increasing and which are now widely used in EVs, particularly in entry-level models, albeit at the expense of energy density.

Efforts to close the battery supply chain have focused primarily on battery recycling using pyrometallurgical and hydrometallurgical processes. These processes can recover more than 95% of the cobalt, nickel, and copper contained in spent batteries and sometimes recover lithium. However, current recycling processes are energy intensive and recover only the cathode material or about 32% in mass of the total spent batteries. Progress in so-called direct recycling[4] has also been made but the process remains a subject of investigation and has not been fully deployed at scale yet. Regarding the recycling process, shredding of spent batteries that are permanently sealed or welded together is the first step of recycling due to the diverse battery form factors, chemistries, and a variety of end-of-life conditions. Unfortunately, shredding mixes the waste streams, and increases the cost of recovery while decreasing the purity of materials eventually separated and recovered. Eliminating the requirement for battery shredding could have beneficial impacts on both recycling costs and purity. This requires reconsidering battery materials and electrolyte selections as well as cells, modules, and packs design and manufacturing.

In addition, as the fraction of valuable cobalt is reduced in the battery materials to decrease the battery price on the front end, the economic viability of battery recycling becomes increasingly questionable on the back end.[5] Noteworthy is the fact that collection and transport of spent batteries account for a significant fraction (~40%) of the total recycling cost. In the United States, spent EV batteries are considered a Class 9 hazardous waste that need to be handled with special precautions, which further adds to the transportation cost.[6] Moreover, 40% of new internal combustion engine cars sold in the U.S. end their life abroad, mostly in Latin America.[7] If the same statistics hold true for the EVs sold in the U.S. in the near future, the recycling industry won't be able to recover these spent batteries, thereby making

[2] V. Henze, Lithium-ion Battery Pack Prices Rise for First Time to an Average of $151/kWh, BloombergNEF, Dec. 6, 2022.

[3] S. M. Fortier, N. T. Nassar, G. E. Graham, J. M. Hammarstrom, W. C. Day, J. L. Mauk and R. R. Seal, USGS critical minerals review, *Mining Engineering*, **74** (5), 34-48 (2022).

[4] L. Gaines, Q. Dai, J. T. Vaughey, S. Gillard, Direct Recycling R&D at the ReCell Center, *Recycling*, **6** (2), 31 (2021).

[5] L. Lander, T. Cleaver, M. A. Rajaeifar, V. Nguyen-Tien, R. J.R. Elliott, O. Heidrich, E. Kendrick, J. S. Edge, G. Offer, Financial viability of electric vehicle lithium-ion battery recycling, *iScience*, **24** (7), 102787 (2021).

[6] L. Gaines, L. Richa, J. Spangenberger, Key issues for Li-ion battery recycling. *MRS Energy & Sustainability* **5**, 12 (2018).

[7] C. Stokel-Walker, This Is where dirty old cars go to die, Wired Magazine, May 19, 2022.

the creation of a domestic and circular battery supply chain virtually impossible.

Furthermore, the pyrometallurgical recycling process consumes a significant amount of energy to operate at temperatures above 1000 °C while emitting large quantities of greenhouse gases and toxic fumes (e.g., HF from the decomposition of PVDF binder and lithium salts containing fluorine). The hydrometallurgical recycling process operates near room temperature but consumes energy and chemicals to dissolve the black mass in acids and to perform solvent separation and salt precipitation. This process results not only in greenhouse gas emissions but also in the production of toxic sludge. Both recycling processes produce large quantities of waste that needs to be disposed of in landfills.

Given the economic and technical challenges of dealing with batteries at the end of their life, ARPA-E is interested in innovations that will mitigate disposal of EV batteries in full, or in part, in landfills. Such disposal is common with consumer electronics, and lithium-ion batteries are responsible for two thirds of the fires at landfills and materials recovery facilities (MRFs) in the United States due to cell puncture and subsequent exposure of reactive components to the atmosphere during trash handling.[8] These fires are very challenging for first responders to extinguish and can last for days and even weeks due to the presence of methane from decomposition of organic waste in landfills. In addition, battery fires produce toxic smoke and often require the closure of the MRFs for weeks and the evacuation of communities surrounding landfills, often disadvantaged.

Finally, a potential program would aim to de-risk and demonstrate novel technologies to facilitate their rapid adoption and the associated procurement decisions; to capture additional value from products and/or materials; and to enable frequent and continuous engagement with customers. The performance and safety of the developed technologies should match or exceed current standards and practices.

Example of technologies of interest

Lead acid batteries suffer from lead sulfate ($PbSO_4$) crystal formation on the Pb electrode during discharge. Upon deep discharge or if the battery is left discharged for a long time, a hard and thick layer of $PbSO_4$ can grow and significantly reduce the battery performance. Several methods have been demonstrated to reverse the $PbSO_4$ formation and regenerate the Pb electrode. For example, pulse conditioning consists of imposing a high voltage pulse which electrochemically reverses the $PbSO_4$ formation reactions without causing excessive heating. Alternatively, adding chemicals, such as the commercial product Thermoil De-Sulfater™, to the sulfuric acid electrolyte can remove the $PbSO_4$ layer. ARPA-E is interested in learning about other battery materials, electrodes, and/or electrolytes that can be regenerated in similar ways but with energy and power densities matching or exceeding those of LFP.

Battery pack assembly based on compression technology such as the designs offered by Aceleron Energy do not have permanently bonded components.[9] Rather, electrical connections between LFP cells and conduction plates is achieved by compression provided by a system of fasteners holding the pack together. Consequently, the cells, battery management system, and heat sink components can be easily disassembled, serviced, and upgraded. All the pack elements can be independently reused, refurbished, or remanufactured while the modular nature of the design makes it scalable. The design also facilitates replacement of faulty cells and eventually their recycling, considered as the step of last resort in achieving circularity.

Note that the examples provided are illustrative, and not intended to be limiting. ARPA-E is seeking

[8] C. Staub, MRF-operator: lithium-ion batteries are ticking time bombs, Resource Recycling, May 20, 2022.
[9] Aceleron Limited, Battery pack assembly, United States Patent Application US 2022/0059898 A1, Feb. 24, 2022.

information on approaches that can meet the program objectives.

Information not requested at this time include:

- Concepts that focus on supplying critical minerals for battery fabrication.
- Concepts that focus on existing battery recycling processes including direct recycling.
- Concepts that focus on conventional lead acid batteries.
- Solutions that focus on incremental improvements in commercial technologies, incremental improvements in control systems for commercial technologies, or incremental improvements in operation or maintenance procedures.
- Large-scale demonstration projects of existing technologies.

Please carefully review the REQUEST FOR INFORMATION GUIDELINES below. Please note, in particular, that the information you provide will be used by ARPA-E solely for program planning, without attribution. **THIS IS A REQUEST FOR INFORMATION ONLY. THIS NOTICE DOES NOT CONSTITUTE A FUNDING OPPORTUNITY ANNOUNCEMENT (FOA). NO FOA EXISTS AT THIS TIME.**

Purpose and Need for Information

The purpose of this RFI is solely to solicit input for ARPA-E consideration to inform the possible formulation of future research programs. ARPA-E will not provide funding or compensation for any information submitted in response to this RFI, and ARPA-E may use information submitted to this RFI without any attribution to the source. This RFI provides the broad research community with an opportunity to contribute views and opinions.

REQUEST FOR INFORMATION GUIDELINES

No material submitted for review will be returned and there will be no formal or informal debriefing concerning the review of any submitted material. ARPA-E may contact respondents to request clarification or seek additional information relevant to this RFI. All responses provided will be considered, but ARPA-E will not respond to individual submissions or publish publicly a compendium of responses. **Respondents shall not include any information in the response to this RFI that could be considered proprietary or confidential**.

Responses to this RFI should be submitted in PDF format to the email address **ARPA-E-RFI@hq.doe.gov** by **5:00 PM Eastern Time on Monday, April 3.** Emails should conform to the following guidelines:

- Please insert “Response to RFI-DE-FOA-0003027 - <your organization name>” in the subject line of your email.
- In the body of your email, include your name, title, organization, type of organization (e.g. university, non-governmental organization, small business, large business, federally funded research and development center (FFRDC), government-owned/government-operated (GOGO), etc.), email address, telephone number, and area of expertise.
- Responses to this RFI are limited to no more than 10 pages in length (12-point font size).
- Responders are strongly encouraged to include preliminary results, data, and figures that describe their potential materials, designs, or processes.
- Where possible, please provide the question number and question text you are responding to.

Questions

ARPA-E is interested in surveying stakeholders interested in achieving circularity of the battery supply chain outside of recycling within the scope of approaches outlined above. The questions posed in this section are classified into several different groups as appropriate. Please provide responses and information about any of the following. ARPA-E does not expect any one respondent to answer all, or even many, of these prompts. Simply indicate the group and question number in your response. Citations are encouraged as appropriate. Respondents are also welcomed to address other relevant avenues/technologies that are not outlined below.

<u>I. Degradation prevention/suppression in battery materials and performance reversibility</u>

1) Batteries degrade for different reasons depending on the selection of electrode materials, electrolytes, cell design, and/or the cycling conditions.
    a. What degradation mechanisms of battery cells can be partially or fully reversed? Please clearly specify the material system(s) and discuss the corresponding primary degradation mechanism(s) that can be affected.
    b. Within the context of 1a), what methods could be employed at the material, electrode, electrolyte, and/or cell level to delay, suppress, or reverse degradation so as to restore the initial performance? Would disassembly of the battery be necessary for this regeneration? Do there exist any compelling proofs-of-concept in the technical literature or elsewhere?
    c. Do sensing methods capable of detecting such degradation mechanisms exist? If yes, please discuss the method(s) in detail including specific capabilities, sensitivities, and limitations.
2) What tools would need to be adopted, improved, or developed to qualify a remanufactured or refurbished battery for reuse?

<u>II. Design for refurbishing and manufacturing of cells and modules</u>

3) What material, design, and manufacturing methods can be used to reversibly seal individual battery cells? Then, how could the cathode, anode, and separator be separated, and the electrolyte recovered?
4) What are some reversible and/or more energy efficient and low carbon footprint alternative manufacturing methods to permanent joining techniques (e.g., welding and soldering) used currently during battery manufacturing? What are their limitations in being used for battery manufacturing?
5) What design and manufacturing approaches could be implemented to facilitate disassembly, reuse, refurbishment, and remanufacturing of battery cells, modules, and packs?
6) What would be needed to reconfigure existing battery production lines to accommodate new, sustainable design(s) of battery cells, modules, or packs? Please contemplate cost, scalability, engineering challenges, and timeline for adoption in the response.
7) What is the state of human-robot interaction? How can it be leveraged for automatic disassembly of spent battery packs and cells?
8) What are the technological, economic, or business hurdles to adopting the new sustainable design of battery cells, modules, and packs that would emerge from the envisioned program? How might these challenges be overcome?
9) What are the technological, economic, and/or business hurdles to using swappable batteries in EVs during normal operation and/or at the battery's end of life? How might these challenges be overcome? Is one transportation modality more amenable to swappable batteries than others and why?

III. LCA and circularity metrics

10) In your opinion, if a technology program focusing on the above-mentioned concerns were to be developed further, what would be the most impactful technical metrics to consider, and why?
11) What metrics might be used to assess the profitability impact of moving towards more circular business models?
12) What metrics might be used to assess the environmental impact of manufacturing and/or servicing battery cells and packs?

IV. Technoeconomic analysis and economic opportunities

13) What are the business benefits and opportunities in achieving a circular and domestic battery supply chain?
14) To what extent are circularity metrics considered in an OEMs' product design and procurement decisions?
15) What are the key technical and economic drivers and obstacles in deciding to redesign parts and components of EV battery packs and the associated manufacturing process(es)?
16) Does the prospect of robotaxis and other shared mobilities or the emergence of customers with large fleets of EVs affect the way OEMs approach battery material selection, rejuvenation/refurbishing opportunities, and design and recyclability of battery modules and packs?