Sustainability perspectives on lithium-ion batteries

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For the last four years, I have had the immense privilege of serving as an Associate Editor for Clean Technologies and Environmental Policy. This opportunity has provided a front-row seat to compelling research aimed at solving global sustainability challenges and a chance to correspond with and learn from authors and reviewers from around the world. The experience has also provided a fascinating education on the scholarly publishing domain and on a wide array of clean technology topics, from the first paper I managed as editor, a techno-economic assessment of biogas-to-hydrogen production (Montenegro Camacho et al. 2017), to a recent contribution on the climate mitigation potential of eco-industrial parks (Zhang et al. 2020). I am humbled and honored by this experience and am grateful for the hard work and patience of all of our hard-working contributors.

As I wind down my Editorial activities this fall, I will also be wrapping up a significant phase of my own research. For the last seven years, my research group has been studying the sustainability challenges surrounding lithium-ion batteries and their end-of-life management after use in electric vehicles, thanks to funding provided by the National Science Foundation through the Faculty Early Career Development Program (CBET 1254688). This project was motivated by the growing adoption of electric vehicles as a strategy to mitigate global fossil fuel dependence and greenhouse gas emissions from conventional vehicles powered by internal combustion engines. Widespread vehicle electrification hinges on concurrent development and cost effectiveness of energy storage systems, like lithium-ion batteries. Research on novel battery materials, designs, manufacturing, and performance has expanded rapidly in the last decade, yet has only begun to comprehend the potential sustainability challenges inherent to this system.

Sustainability challenges span the entire technology life cycle for energy storage systems like lithium-ion batteries (LIBs): from raw material extraction, battery manufacturing, electric vehicle use, and management of LIBs at end-of-life. Raw material impacts typically stem from the resources that provide LIBs with their necessary electrochemical functionality, including the typically graphitic anode and the cathode, which is usually comprised of lithium, cobalt, nickel, and manganese in varied concentrations. While early attention was focused on lithium availability, recent research has demonstrated that cobalt may actually present the greatest concerns with respect to sustainability and long-term availability. Cobalt is primarily sourced in the Democratic Republic of the Congo, a region historically characterized by political instability, social impacts in the mining sector, and lack of supply chain transparency. The global reliance on such a concentrated supply chain introduces risks of resource shortages or price spikes due to disruptions, which may translate to downstream impacts on battery and even vehicle price competitiveness (Leader et al. 2019). Ensuring a long-term, stable supply of cobalt will require expanding the geographic diversity of the supply chain while at the same time developing secondary sources to be obtained through increased recycling (Fu et al. 2020).

Efforts to minimize LIB material and manufacturing impact have also been focused on new electrode designs and alternate materials that alleviate cobalt demand and provide performance advantages, such as higher energy and power density or longer lifetime (e.g., Wu and Kong 2018). Such innovations may lead to a slightly greater upstream environmental impact but pay off by significantly reducing electricity consumption and losses during charging and discharging over the battery's useful life in electric vehicles. These advances also promise to dramatically extend battery lifespan, prompting recent claims by Tesla CEO Elon Musk that a "million-mile battery" is within reach. However, even LIBs with extended lifespans will ultimately require management once they no longer meet the technical specifications for use in vehicle applications. Researchers believe that these systems will still have significant energy storage capacity

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remaining at this point, thus motivating further research to study sustainable avenues for retaining material and energy value contained within LIBs.

The recent focus of our research has been on understanding how circular economy principles can guide sustainable management of the growing stream of end-of-life LIBs via a hierarchy of recovery pathways: direct reuse of used LIBs in vehicle applications, cascading reuse in less demanding energy storage applications, material recovery through recycling, and finally, sending a minimal amount of material to downstream disposal. Of these options, cascading reuse of batteries in energy storage applications appears to have the greatest economic and environmental promise (Richa et al. 2017a). Such reuse applications may include fast charging stations for electric vehicles (Kamath et al. 2020), utility-scale electric load leveling (Richa et al. 2017b), or back-up power supply during natural or human-induced disasters (Moore et al. 2020). Each of these reuse pathways offers the potential to minimize the magnitude and pace of LIB waste generation while at the same time reducing life cycle environmental impacts of energy and vehicle systems.

Despite the promise of circular economy solutions for end-of-life LIBs, many unknowns still limit widespread adoption. For instance, batteries will have highly variable states of health and residual capacity after use in electric vehicles, as influenced by how and where they are driven and charged during that first life. Thus, research needs include methods for rapid testing to assess reuse potential, risk analysis to better understand how to transport and configure LIBs safely in their downstream applications, and remanufacturing techniques to repair or recover battery cells or modules (e.g., Liu et al. 2016). While battery recycling is mandated by policy in some regions, such as the EU Batteries Directive, reuse is typically not an explicit goal of policy mechanisms. Both regulators and manufacturers face uncertainty of how to foster value-retaining reuse while minimizing liability transfer between the first and second LIB application. Further, any such solution has to be rigorously analyzed from a systems perspective (as discussed in a prior editorial; Babbitt 2017) to ensure that solving one problem does not introduce unintended consequences.

Even as this chapter of my research and editorial activities comes to a close, I am excited about the discoveries still to come. Many of the technology and policy challenges surrounding a circular economy for LIBs are well suited to be addressed by readers and authors of this journal:

- Synthesis and testing of high performance electrode materials that are not reliant on scarce resources;
- Frameworks that inform life cycle design of batteries, including lifespan extension, reuse, repurposing, and recycling;

- Advanced battery diagnostic tests and remanufacturing techniques;
- Novel recycling systems that target high value materials, including lithium, cobalt, nickel, and manganese; and
- Systems-level economic and environmental assessments that comprehend potential sustainability tradeoffs.

These contributions are critical if energy storage technologies are to reach their full sustainability potential. Such studies will also enable Clean Technologies and Environmental Policy to continue its trajectory of growth in impact and global reach. I look forward to reading these contributions and continuing to serve as part of this community of scholars, even from the other side of the editorial desk.

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