The sustainability of battery technologies - today and tomorrow

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The widespread adoption of Li-ion battery technology has been accompanied by significant challenges associated with all stages of their production and use, from the sustainability of the material supply chain, to manufacturing, end-of-life processing and recycling. In this editorial, we discuss some of the approaches taken to address the sustainability of Li-ion batteries, and describe some of the emergent systems that may provide long-term alternative energy storage solutions.

Li-ion batteries (LIBs) have reshaped the modern world. They are widely used in consumer electronics, stationary energy storage facilities and, increasingly, in our cars. The rapid proliferation of the technology has been coupled with significant enhancements in battery performance, stability and safety. However, as the technology advances and enters increasing numbers of applications, sustainability challenges are now front-and-centre, and span the availability and processing cost of raw materials, the economics and waste-generation associated with battery manufacture, and end-of-life device and component management.[1]

LIBs typically consist of a graphitic negative electrode and a positive electrode based on transition metal oxides (TMOs), usually Co, Ni and Mn in variable ratios. The majority of global Li reserves are found in the salt flats of Chile, Bolivia and Argentina and, while there has been a number of significant sustainability issues (socioeconomic and environmental) raised by the mining process, Li availability is generally projected to meet long-term demands.[2] The more pressing concern, however, is the availability of Co. More than half of mined Co output originates in the Democratic Republic of Congo, a region with a history of political volatility and problematic mining practices.[3] It is obtained as a biproduct of Cu mining, resulting in a complex supply and demand relationship. Intensive processing is required to extract the pure metal from ore and is predominantly performed in China, adding an additional geopolitical consideration to the supply chain. All of the above can lead to erratic fluctuations in price,[4] although this has been partly mitigated by increased market transparency since Co was listed on the London Stock Exchange. Regardless, the questionable long-term sustainability of the Co supply chain is now widely acknowledged.

There is an increasing drive to move towards low-Co or even Co-free electrodes for Li-ion batteries. The use of $LiFePO_4$ (LFP) as a Co-free LIB positive electrode intercalation material was introduced by Goodenough in 1997.[5] LFP exhibits excellent thermal stability and cycle life, but lower volumetric energy density, rendering it a poor option for automotive applications.[6] A possible solution to improving energy density of the electrode is to use low-Co, layered mixed-type metal oxides such as $LiNi_{0.333}Mn_{0.333}Co_{0.333}O_2$ (NMC111) and its homologues $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC622) and $LiNi_{0.8}Mn_{0.1}Co_{0.1}O_2$ (NMC811). These systems store more energy than Co-based layered oxides and LFP, but suffer from lattice distortion and stability issues upon cycling; challenges that are now being addressed by researchers in the materials and nanoscience communities.[7] The development of new positive-electrode materials for LIBs is generally considered to be the most promising strategy to reduce reliance on the Co supply chain, but is likely to lead to increased pressure on the supply of replacement component materials such as Ni.[8]

Given that the uptake of new types of positive-electrode materials will shift, rather than eliminate, supply chain challenges, their use should be combined with a coherent circular-economy approach to LIB re-use and recycling. As the global number of electric vehicles (EVs) is expected to increase from around 8 million in 2019 to 140 million (and 7 % of the global fleet) by 2030,[9] such an approach is important from both a waste-management perspective and as a vital part of the (re)supply chain. Approaches to LIB recycling can be grouped into those that allow recovery of the constituent materials of the battery (pyrometallurgical and hydrometallurgical) and those that focus on removal of intact electrode material for incorporation into a new cell (direct recycling). Pyrometallurgical and hydrometallurgical approaches allow effective recovery of the metals that make up the electrodes and current collectors (typically Co, Ni, Mn, and Cu), through treatments in high temperature furnaces and aqueous solvents, respectively. In contrast, direct recycling involves the direct recovery and reconditioning of the positive- and negative-electrode materials.[10] A TMO recovered from a positive electrode will typically require re-lithiation due to degradation associated with battery cycling but can essentially be transferred into a re-manufactured LIB without major changes to its morphology. The type of recycling employed depends on the nature of the battery pack and the specific chemistry of the system. For example, around 70% of the cathode value in Co-rich electrode materials such as $LiCoO_2$ can be recovered using pyrometallurgical and hydrometallurgical approaches, but the economic benefit is significantly lower in low-Co systems.[11] For most positive-electrode materials, direct recycling is the most economically viable approach. As well as component recycling strategies, the reuse of LIBs is becoming an increasingly important aspect of the LIB circular economy. EV batteries are typically 'retired' when their capacity drops below 80% of their rated level.[12] This leaves a huge number of end-of-first-life batteries that can potentially be readily reused in stationary energy-storage systems, such as utility-scale grid, EV charging stations, or telecommunication towers. A number of flagship projects are already underway in these sectors.[13]

Sitting alongside the growing need for improved LIB recycling technologies and the standardization of reuse strategies sits a clear scientific goal: the development of a fundamentally more sustainable battery that mitigates issues of supply chain volatility and material abundance while delivering performance surpassing that of LIBs. Next-generation batteries that do not rely on strategic elements such as Li, Co, and Cu could facilitate a shift towards sustainable industrial models. We note that all future battery technologies face significant scientific challenges, which have been reviewed elsewhere,[14-18] but here we consider the potential impact of the technologies, assuming these challenges are overcome. The Na-ion battery, for example, does not typically require Co in the positive electrode, instead employing Mn, Ni, V and Fe materials, among others.[16] Moreover, the Cu current collectors required in LIBs can be avoided.[19] Consequently, widespread use of Na-ion batteries has the potential to alleviate bottlenecks in the battery supply chain and pressure on specific metal reserves. However, improvements in sustainability are dependent on Na-ion technology reaching similar performance levels to that seen in LIBs.[20] In addition, while Ni and Mn are more abundant than Co, both underpin major industries (for example, Ni is used in stainless steel manufacturing),[21] which could pose a challenge in the event of significant market growth due to EV uptake. A tantalizing alternative is to replace intercalation-based electrodes completely and perform redox reactions on biomass and earth-abundant charge carriers. For example, in Li-air,[14] Li-S,[15] and organic radical batteries,[18] the redox reaction at the positive electrode occurs on a non-metal center, thus avoiding the use of TMs entirely. The adoption of such systems would greatly simplify any future industrial supply chain and remove geographical inequalities in the battery and energy market. Moreover, these technologies could potentially also cause a step-change in specific energy and power, a critical stepping-stone for the electrification of the aviation industry.[22] However, a note of caution – cell energy per g of Li is lower in these batteries compared to LIBs due to the lower cell voltage, so additional strain will be placed on the Li supply chain and recycling and reuse would become even more critical should Li-air and Li-S batteries be taken up at scale.

The complex sustainability, economic and geographical landscape of the battery industry and global markets means that no one solution will address the sustainability issues associated with the growth of battery and battery-reliant industries. Close links between mining, processing and manufacture are needed for a sustainable and economically viable battery manufacturing industry. For LIB technology, this will always be challenging in countries without access to significant metal reserves. Consequently, existing battery supply chains and manufacturing are strongly dependent on the socio-political dynamics of relatively few countries. The immediate future of the battery sector is likely to involve increased industry focus on reducing the environmental impact of spent batteries through the development of biodegradable or environmentally benign cell components;[10] indeed, aqueous rechargeable batteries are a promising system from this perspective.[22] The circular recycle-reuse economy, where critical materials are recovered from spent batteries as a matter of course and end-of-first-life battery packs are repurposed in a range of stationary energy storage settings, is also likely to become increasingly important in the future. A little further down the line, the next generation of battery technologies will herald a move away from critical elements towards cheap and abundant materials, improving supply-chain sustainability, opening up new applications for secondary batteries, and separating energy storage science from the influence of global politics.

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