JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Charging Sustainable batteries

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Abstract

Having transformed our way of life, rechargeable batteries are poised for exponential growth over the coming decade, notably due to the wider adoption of electric vehicles. An international expert panel proposes a combination of vision, innovation and practice for feasible pathways toward sustainable batteries.

Keywords: Renewable, Fossil fuels, Interface, Electrolyte, Sodium – ion batteries, Conventional energy, Fire extinguishing agents.

Introduction

The fast-growing global energy demand calls for an increase in renewables and nuclear power to replace fossil fuels, with the aim of reducing carbon footprints and addressing climate change. According to the US Energy Information Administration, renewable energy consumption will be close to the share of liquid fuels, leveling at ~250 quadrillion BTU in 2050 (ref. 1). Although renewable energy sources, such as solar and wind energy, are preferable from an environmental perspective, they suffer from intermittent storage that cannot cater to a constant supply chain. Electrochemical energy storage devices — in particular lithium-ion batteries (LIBs) — have shown remarkable promise as carriers that can store energy and adjust power supply via peak shaving and valley filling. In view of the importance of LIBs, the Nobel Prize in Chemistry was awarded to John B. Goodenough, Stanley Whittingham and Akira Yoshino in 2019 for their pioneering contribution to LIBs[2]. Indeed, LIBs have revolutionized our lifestyle and their further developments could transform society towards a more sustainable future.

The global electric vehicle (EV) stock grew to 10 million in 2020, and 160 GWh LIBs were produced to power these electric cars[3]. With deeper EV penetration, global lithium demand has reached a new record (345,000 metric tons of lithium carbonate equivalent in 2020). There could be serious shortages of lithium, often labelled as 'white gold', in the near future[4]. In this sense, a re-examination of recycling strategies is essential[5], and recycling also presents an opportunity for batteries to reduce socio-economical risks in relation to non-domestic supply chains in each country. Clearly, it is indispensable to design, manufacture, use, dispose and recycle batteries in a sustainable way. Battery R&D tends to fall into two categories: maximizing energy density for transportation, and minimizing energy storage. Although significant progress has been made over the past three decades, it seems like the energy density of conventional LIB technologies is starting to reach an asymptotic limit. Partially supplementing current electrodes with alternative high-capacity materials is a popular approach for most battery manufacturers. More recently, the use of lithium metal as an anode has been revived. When coupled with solid-state electrolytes, this can potentially offer high storage density[6]. On the cathode side, lithium cobalt oxide ($LiCoO_2$) continues to dominate the high-end portable electronic battery market because of its high energy density, while cobalt-reduced or even cobalt-free cathode chemistries, such as $LiNi_xMn_yCo_zO_2$ (NMC), $LiNi_xCo_yAl_zO_2$ (NCA) and $LiFePO_4$ (LFP), are widely used in EVs. Novel cathode materials, such as sulfur and oxygen, have also been intensively investigated. However, they suffer from relatively shorter lifetimes and lower roundtrip energy efficiencies, although they show significantly higher theoretical specific capacity.

Compared to traction batteries, battery technologies for grid-scale energy storage would not prioritize energy density. Considering the extremely competitive market, beyond-lithium-ion technologies have received considerable attention. Among them, sodium-ion batteries are a potential alternative, owing to more abundant sodium resources and similar working mechanism to LIBs. In contrast, aqueous electrolyte-based rechargeable batteries, such as redox flow batteries, are much closer to entering the stationary energy storage market.

Conventional battery materials recycling strips the batteries down to their electrode and electrolyte components for reuse. Here, the nature of the electrolyte (liquid versus solid) and the associated interface with the electrodes define the ease of separation, which differs for a LIB versus a solid-state battery (SSB). Ceramic solid electrolytes based on metal oxide, sulfide or sulfide compounds are attractive for use in SSBs as they offer the potential to enable high energy densities by using pure lithium or alloys as the anode.

However, a change in electrolytes will require alternative strategies in recycling. These are driven not only by a wider range of rare earth and transition metal ions in the solid electrolyte (for example, $Li_7La_3Zr_2O_{12}$, thio-LISICON (lithium superionic conductor), LIPON (lithium phosphorus oynitride) or Li-argyrodite) when compared to their liquid counterparts, but also by the manufacturing processes required to form a coherent interface and low interfacial resistances in case of solid– solid electrolyte–cathode interfaces. Recent reports discussed thermal budgets and pressure requirements that are needed for solid electrolyte separators to assure good bonding for fast lithium transfer across the solid–solid interfaces[6,7]. Separating a liquid electrolyte from the cathode may appear as the natural and easier choice in terms of recycling. However, it is clear that when moving towards SSBs, any strategy that can lower the co-bonding temperature during manufacturing is an important parameter to tune — not only to lower theoverall processing costs, but also to facilitate separation for recycling[7].

Safety forms an important dimension of battery sustainability. Accidents are unwanted where the batteries undergo thermal runaway, especially due to internal short circuits within the flammable organic electrolyte. Traditional fire-extinguishing agents, such as water or dry powders, cannot efficiently extinguish LIB fires. It is important to specifically consider and design fire-extinguishing agents and the corresponding intelligent systems to deploy them. Alternatively, non-flammable electrolytes, either liquid or solid, may be practical solutions to improve safety.

For example, it has been shown that concentrated aqueous electrolytes can also have a wide potential window, where optimization of the electrode–electrolyte interfaces can play a critical role in enabling comparable energy densities to the-state-of-art LIBs[8]. To avoid the high cost and potential toxicity associated with highly concentrated fluorinated lithium salts, development of a high-voltage aqueous electrolyte with low salt concentrations using low-cost and eco-friendly materials is a promising solution. For all-solid-state cells, the interfaces remain a significant challenge.

Today, SSBs still suffer from resistive solid– solid contacts, undesirable side reactions at interfaces, and low power density and cycling performance. However, SSBs are showing fast improvement, with significant commercialization efforts ongoing9.

As the quantity of LIBs produced reaches thousands of gigawatt hours, the accumulation of end-of-life (EOL) batteries may become similar to that of electronic waste in early 2000s (ref. 10). Currently, LIBs are mainly produced in China, Korea and Japan. Will EOL batteries flow back to Asia? Who should take responsibility for EOL battery disposal? Consumers, battery manufacturers or vehicle manufacturers? Regarding EOL regulations, a battery trace system could be developed for every single cell from the beginning of manufacturing, considering that we already have big-data technology with integrated traceability enabled by the Internet of Things. In addition, it is important to build an EOL battery trade system, where entrepreneurs can profit from EOL batteries. It is also not clear yet whether EOL battery materials should be reused in a new battery, or whether alternative integration pathways in other goods may be a profitable and sustainable pathway for their reuse. For example, there exists a significant opportunity for repurposing battery packs and cells that have reached unacceptable levels of degradation for EV applications (for example, capacity and/or power fade) but may still work for applications where high energy or power densities are less critical, such as stationary storage. An international association should clearly be launched soon for global EOL battery disposal to achieve these goals.

Regarding recycling technologies, processing EOL battery materials will be more complicated and challenging than electronic waste, given the compound chemistries and energy costs related to separation. Another critical aspect unique to EOL batteries is the latent energy content if batteries enter the EOL materials stream without being fully discharged, with corresponding risks that arise during transportation and mechanical disassembly. For instance, some components, such as cobalt-based cathodes or organic electrolyte-related chemicals, are toxic — potentially generating harmful impact on the natural environment and human health, and therefore requiring special protocols. Following the previous analogy of electronic waste, it is conceivable that relevant streams of EOL batteries will be recycled in informal (artisanal) ways without any control of emissions or toxic exposure to workers. Therefore, it is important to ensure that the recovery of batteries and their recycling occur in authorized installations that identify, evaluate and properly manage emissions and wastes, as well as occupational health and safety hazards.

In this Comment, we share our considerations on important aspects of sustainability in relation to batteries. Our international expert panel (see Box 1) suggests that future 'sustainable batteries' need to be designed and manufactured in

line with the principles of sustainability, considering every single component within the whole process chain and the required resources, including conscious choices for materials composition and mining origins. The composition and architecture of sustainable batteries must anticipate EOL, and allow for an easy and as complete as possible disassembly and materials extraction process, with low (additional) energy and materials input.[11]

Environmental, economic and social sustainability considerations should be quantitatively assessed with life-cycle assessment (LCA), life-cycle costing (LCC) and social life-cycle assessment (S-LCA), respectively. There are numerous studies available for current LIB chemistries, but also for emerging battery systems including sodium- or magnesium-based chemistries[12,13]. Generally, the results show that all life-cycle stages (raw materials provision, production, use, second use and recycling) are important and should be addressed together. In addition, rapid development of the sector requires frequent updates of these studies, considering the improvements that have been —

and will foreseeably be — achieved in terms of performance and sustainability. Improved data availability, as well as production and technology improvements, is reflected in LCA studies, which have recently reported a trend of decreasing environmental impacts[14]. Regarding the variety of battery chemistries available, a general outcome is that there is no single ‘silver bullet’ battery — that is, one that performs best in all applications and conditions under a life-cycle-based sustainability perspective. Rather, the optimal choice depends strongly on the specific requirements of the targeted application and also on the individual weighting that is applied to the various dimensions of sustainability.

Despite the considerable number of studies in this field, a major problem remains the limited availability of transparent industry-based data, and also the specific differences across individual manufacturing plants — for example, in terms of energy demand and origin[14,15]. Many existing works rely on secondary information from other publications and only a few actually use original primary data[15–18]. This leads to error propagation and reduces the reliability and robustness of several of the existing studies. In addition, there is often a lack of transparency in many battery studies, which hinders

the traceability of the results. Efforts are therefore needed from within the scientific community and industrial stakeholders to move towards transparent, open and comprehensive studies based on primary data, disclosing all data in a readily reusable format that future analyses can be based on[19]. Only in this way can the results support scientifically sound and knowledgebased decision making, while keeping pace with the rapid technology development.

With massive deployment of EVs and energy storage systems looming, it is important to assure a sustainable and careful materials selection that is suitable for recycling, while also adopting high safety standards. The supply-chain risks need to

be minimized through smart choices in the chemistry, and manufacturing decisions for cell and pack design should ensure opportunities for recycling and reuse. Meanwhile, I must improve and integrate all aspects of sustainability (that is, social, economic and environmental aspects) in battery assessment, and integrate them as key elements within a full circular economy. This motivates clear, world-wide policies that concern more sustainable battery production, use and disposal (in addition to the existing regulations and directed flows for electronic waste). It is also important for consumers to be able to make eco-conscious choices for their battery recycling strategies at the time of purchase. We believe that continuous development in battery technology and energy storage will bring exciting breakthroughs not only in the new electrode or electrolyte materials, but also in the next generation of battery systems[20].

Acknowledgement

I am very much thankful to Prof. (Dr.) U.S. Yadav, Rtd., HOD, Deptt. Of Chemistry, J.P.U. Chapra, Prof. Udai Arvind, Dean Sc. JPU Chapra, Prof. (Dr.) Rabindra Singh, HOD, Deptt. Of Chemistry, J.P. University, Chapra, Dr. Sanjay Kumar, Asso. Prof. Deptt. of Chemistry, Jagdam College, Chapra for sharing their technical support and valuable suggestions in this regard,

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