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Voices

Technological pathways toward sustainable batteries

Batteries are essential if we are to realize an electrified, low-carbon future, but battery technologies are not presently sustainable. This Voices asks: what are the emerging technological solutions to improve the sustainability of batteries?

Arumugam Manthiram
Texas Materials Institute, The University of Texas at Austin

A path forward to sustainable batteries

As climate change and environmental concerns escalate, the inevitable solution is the wide adoption of renewable energy (e.g., solar and wind), but these technologies suffer from intermittency problems. Therefore, efficient and economical storage and utilization of electricity collected from renewable energy sources are at the center of green energy revolution. Rechargeable batteries are the most viable option for renewable energy storage and for transportation electrification. Cost, energy density, power density, cycle life, safety, and environmental impact are the major parameters to consider with battery technologies. As electrification and renewable energy use accelerate rapidly, sustainability and affordability of battery technologies will be the most dominant factors without unduly compromising the other parameters. For instance, cobalt use is a problem today due to limited abundance and ethical concerns as well as air pollution associated with mining. Although nickel has become indispensable to replace cobalt, nickel will become a problem tomorrow, and as we move forward, any mined metal, including lithium, will be a problem the day after tomorrow. Therefore, the R&D efforts should engage progressively on eliminating cobalt, nickel, lithium, and any mined metal. This translates to cobalt-free lithium ion (Li-ion) to nickel-free Li-ion or sodium-ion to lithium-sulfur to sodium-sulfur to sodium-organic cathode batteries. Unfortunately, they are currently met with severe performance challenges, such as limited cycle life, which originate from surface instabilities in contact with the electrolyte. Continued basic science research with persistence can ultimately take us where we need to be.

Jodie L. Lutkenhaus
Texas A&M University

Ditch the metal and go organic

Metals are essential ingredients in today's Li-ion batteries, but their continued use presents economic, ethical, and environmental challenges. Projected shortages of cobalt and nickel in the coming decades could cause increased prices, and the global supply chain of these metals, lithium included, is highly localized. The last few years have brought attention to the harsh conditions of and use of child labor in the extraction of some these materials, adding social and ethical concerns. Compounded with the increasing demand for Li-ion batteries brought by the expanding electric vehicle market and rapid digitalization of society, there is an imminent need to address these issues.

One alternative is to replace metal-containing active materials and electrolytes with organics. This metal-free, organic battery could be sourced domestically from biomass, thus democratizing the battery supply chain to allow for more global economies to participate in battery manufacturing from cradle to grave. Furthermore, the infrastructure in place for recycling plastics might be translated to that of recycling organic polymer batteries. To realize this vision, it will be essential to mobilize scientists, engineers, and policy makers to consider not only the performance of a battery but also the human and global imprint throughout the battery's life cycle.

Yongzhu Fu
College of Chemistry, Zhengzhou University

Organic batteries for sustainable energy storage

Li-ion batteries have become an indispensable form of energy storage and power supply in our society today as portable electronics and electric vehicles increase in popularity. However, as the need for a more sustainable battery future becomes increasingly apparent, there is a need to develop batteries that do not rely on unsustainable critical metals such as cobalt and nickel. Organic batteries show promise in this respect. In place of the metals used in Li-ion batteries, the electrode materials in an organic battery are organic compounds containing abundant elements such as carbon, hydrogen, oxygen, sulfur, and nitrogen. These compounds are cheaper and have fewer environmental impacts. However, in organic batteries, the charge storage mechanism usually relies on cleavage and formation of covalent bonds, and the reversibility of redox reactions is related to the inherent features of chemical bonds and conformation of functional groups, and these two facts challenge the battery performance. Furthermore, in organic batteries, high amounts of carbon additives are needed in the electrodes because these organic compounds are usually not conductive. Despite these challenges, progress in electrode materials is being made, including quinones and organosulfur. Recently, organosulfur has attracted significant attention due to the discovery of promising performance demonstrated by the intriguing redox mechanisms. Continuous efforts are still needed to design and synthesize new organic compounds with abundant active sites and also to develop strategies that can enable organic batteries to be used in practical scenarios. In the foreseeable future, organic batteries will become a reality and play an important role in making batteries more sustainable.

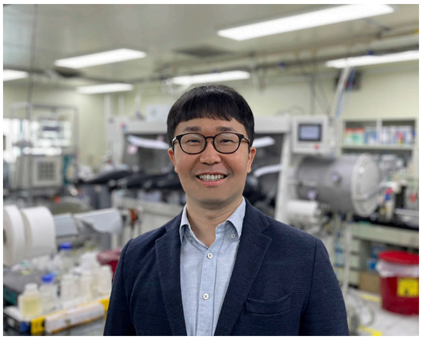
Peng Bai
Department of Energy, Environmental & Chemical Engineering, Washington University

Anode-free batteries offer sustainable alternative

Graphite, the anode material for Li-ion batteries, stores lithium ions during recharge and releases them to power our cellphones, laptops, and electric vehicles during discharge. Although electric vehicles hold the promise to decarbonize transportation, the mining and processing of battery-grade graphite at the scale of close to a million of metric tons each year have strained our ecosystems through pollution and greenhouse gas emissions while also creating socioeconomic and ethical challenges within and beyond mining communities. The situation will only get worse with the rapid expansion of battery production worldwide until we take a simple action: removing graphite from batteries.

An Li-ion battery without the graphite anode can still function, with the only the difference being that lithium ions from the lithiated cathode that would normally intercalate into graphite during recharge instead becomes metallic lithium on the anode-side current collector. Furthermore, anode-free batteries (AFBs) have much higher energy densities than do Li-ion batteries, and the absence of an anode also leads to substantial cost reduction.

The state-of-the-art anode-free lithium batteries are beginning to exhibit high cycling efficiency under practical operating conditions, where the nonuniform lithium metal plating is the root cause of early failures. Surprisingly, earth-abundant sodium, the closest relative in the alkali metal family, has exhibited an ideally stable performance in the anode-free configuration. Insights into the interfacial solvation structures, interphase formation, and microscopic charge transfer kinetics are leading the way to enable other anode-free batteries for a more sustainable future.



Byung Gon Kim
Korea Electrotechnology Research Institute (KERI)

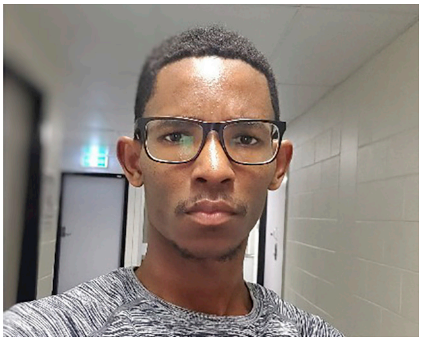
Address Li-dendrite for more sustainable AFBs

With a goal of meeting the Euro 7 standards to reduce air pollution from road transport by 2025, automakers worldwide are racing to manufacture electric-motor-based vehicles. However, for zero-emission vehicles to become popular, they must achieve a driving mileage comparable to that of internal-combustion engines, which necessitates the development of next-generation batteries with long-distance driving potential per charge. Among various candidates, AFBs have received considerable attention because they can utilize the existing manufacturing process, and, because of their lithium-anode-free feature, exhibit higher energy density, better safety, and lower costs than do other battery systems that use metallic lithium anode. However, dendritic lithium growth caused by non-uniform lithium deposition induces a decrease in Li efficiency, which can not only impede the storage capacity of AFBs but also increase the amount of wasted AFBs or even increase demand for lithium as a result of shorter battery lifespan, leading to various sustainability challenges. To address these problems, diverse approaches can be followed: (1) a functional electrolyte and protective layer, enabling uniform lithium deposition and robust solid electrolyte interphase layer formation; (2) a highly efficient lithium-confinable host, mitigating volume change and preventing a direct contact between lithium and electrolyte; and (3) compensating for active lithium loss by introducing supplementary lithium, such as a sacrificial cathode. In addition to these approaches, a technological approach controlling the breathing behavior of the cell could be a viable option. If these approaches synergize with each other, the commercialization of more sustainable AFBs will no longer be just a dream.

Seung Woo Lee
George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology

Rubber electrolytes for sustainable batteries

Li-ion batteries currently offer the most practical solution for powering consumer electronics and electric vehicles. However, the increased energy demand is of a concern given the intermittency challenges attached to renewable energy, and, therefore, there is a huge demand for safer and more scalable and energy-dense batteries. Lithium-metal batteries with solid-state electrolytes (SSEs) have been considered the most promising solution to improve energy density and safety. Current lithium-metal battery technologies mostly rely on oxide- or sulfide-based SSEs that have high ionic conductivity. However, oxide-based SSEs require high sintering temperatures, and sulfide-based SSEs can release toxic hydrogen sulfide gas in the air. The manufacturing of these ceramic-based SSEs is therefore complex and energy intensive, posing sustainability challenges. When considering the sustainability of the manufacturing process, solid polymer electrolytes are of particular interest because of their non-toxicity, low cost, and soft characteristics. However, most polymer electrolytes do not have sufficient ionic conductivity and oxidation stability for the reliable operation of solid-state batteries. Recent research has shown a promising approach to solving these issues by demonstrating a 3D interconnected plastic crystal phase with high ionic conductivity within a robust rubber matrix. A new class of rubber electrolytes can be synthesized by a simple polymerization process under mild temperature conditions. This approach is expected to inspire the development of more sustainable organic SSEs for next-generation batteries.



Emenike Okonkwo
College of Science and Engineering, James Cook University; Department of Metallurgical and Materials Engineering, University of Nigeria

Ease of recycling key to sustainability

Rechargeable batteries are undoubtedly key to sustainably meet the continuously growing global energy demand and climate change issues associated with energy generation. Although rapid technological advancement in the past few decades, especially breakthroughs in cathode chemistries, has eased major deterrents associated with deployment of batteries, it has not made modern batteries more sustainable. Sustainability is a tripod construct that goes beyond the use of cheap materials and achieving higher energy density. It entails incorporating circularity in the material flow scheme in contrast to short-term remedies such as elimination of the use of scarce elements. If the finiteness of the lifespan of a typical rechargeable battery (e.g., Li-ion batteries), the quantity of critical or soon-to-be critical materials in batteries, and toxicity of some battery components are placed into perspective, then designing with recycling in view should be the focus of sustainability.

Good design simplifies the recycling process and facilitates ploughing back materials into the material flow system. Although this is widely acknowledged, and efforts such as development of anode-free batteries, water-soluble binders, and battery components from renewable and organic sources such as lignin point to a brighter future, more attention should be paid to the cathode materials and electrolytes because they are the most complex and difficult parts to recycle. Above all, development of greener recycling techniques is essential to reduce the impact of recycling on the cradle-to-grave environmental life impact of batteries.

Reginald M. Penner
Department of Chemistry, University of California, Irvine

Disruptive battery technologies are coming

The explosion of battery research has been so great that it feels as if it's been 20 years rather than three since John Goodenough, Stan Whittingham, and Akira Yoshino were jointly awarded the Nobel Prize for the invention of the Li-ion battery. With this foundational technology, innovation in electrical energy storage has accelerated, fueled especially by our need for better rechargeable batteries for electric cars, trucks, buses, motorcycles, and bicycles. However, existing lithium batteries continue to face technical barriers such as short lifetimes, long charging times, and heavy weights, and they also cost a great deal. An emerging and more prominent challenge is, however, the increasing demand for increasingly scarce critical metals such as cobalt, lithium, and nickel, which creates various sustainability challenges.

The remedies to these problems are already the subject of many hundreds of publications. Unfortunately, the development of practical technologies can be more time consuming than the conduction of the fundamental science in labs. That said, the R&D pipeline is filling up, and better batteries are on their way. The carbon anodes of Tesla lithium batteries are super-charged with silicon particles to increase their energy storage capacity. Earth-abundant sulfur could soon do for lithium cathodes what silicon is already doing for anodes. Lithium ions will compete with the ions of more abundant elements: sodium, potassium, zinc, and magnesium. It won't be long before the venerable "jelly roll" architecture that is presently exploited for virtually all secondary batteries could be replaced by precision 2D and 3D battery architectures, eliminating prominent mechanisms of failure, enabling dramatically enhanced cycle stability, and eventually reducing the dependency on critical metals.