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# Grand challenges and opportunities in next-generation batteries and technologies

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The development of advanced Li-ion batteries and technologies generally addresses one of four objectives: 1) create a higher volumetric energy density and/or specific energy/power, 2) impart intrinsically safer chemistry, 3) produce speedier charging, and 4) utilize less expensive batteries but with competitive/near-competitive performances. Certainly, other factors can play a role as well, dependent on the type of market targeted and the availability of global supplies; however, for widespread adoption, the above points/criteria remain salient. Li-ion is commercially well entrenched in industry for communication and transportation (EV) applications. Nowadays, slight iterations, mostly electrolyte-defined, are incrementally improving safety, cost, and cycle or calendar life. The last point, calendar life, is one that is often overlooked for very high-energy dense Li-ion batteries, because of their reactivity at higher charge (OCV conditions) and elevated temperatures. While cycle life is debated with respect to capacity/energy performance decline, attempts to re-purpose the battery itself or recycle the internal chemical constituents at end of life have considerably grown in the field. Hopefully, energy-neutral processes are also considered in the recycling loop. Nevertheless, the energy storage arena is quite large, and this pursuit hinges on pushing the field in one of many directions, toward loftier objectives. The pursuit of next-generation batteries and technologies must thus delve deeper into new and novel chemistry and electrochemistry to create a world with a neutral, carbon-free environment, and one that is solely sufficient on energy-producing renewables such as the Sun and wind-derived means. The application of electricity and chemistry within our world is thus a 21st century opus.

The introduction of sodium-ion batteries (SIB) onto the battery playing field has taught us the value of foreknowledge of non-aqueous (electro)chemistry spawned from Li-ion, which can speed up research directions and shorten development times. The growth in publications on SIBs has been great over the last 10 years, and this indeed represents a “Beyond-Li-ion” battery system approach; however, one of perhaps lower intrinsic energy density. Energy densities of SIB that approach 250 Wh/kg, or equivalent to the best Li-ion batteries of today’s marketplace are not yet proven/discovered. However, modeling of battery packs does suggest lower costs of production and raw materials extraction as well as lower energy expended for material processing compared with Li-ion (in terms of cost/kWh). It will be interesting and certainly competitive if SIB can achieve costs below that of graphite/LFP ($LiFePO_4$), yet possess equal energy density, life, performance, and safety. On paper this is easy to state, but the challenge is to show this comparison in the field. We look forward to continued development of new SIB cathode and anode materials’ phase space, new electrolytes, salts, and other SIB technologies and features that will draw interest in this quickly developing field.

Because of difficulties in controlling (electro)chemical reactions (side reactions), both interfacially and in the bulk, as well as other ramifications (electrolytes), the pursuit of non-Li-ion alternative battery chemistries can be quite elusive and challenging. New dichotomies, away from Li-ion batteries, exist. One must think "outside the box." In all, the electrode interfaces, their ionic and electronic conduction, passivation, material control, and spatial and mechanical integrity all must work harmoniously in order for the system to function properly and within specifications. Such challenging systems may include the following: 1) Li-air or Li-$O_2$, 2) non-vanadyl redox flow, 3) multivalent batteries: Mg, Ca, Al, 4) dual-ion systems, and 5) fluoride anion batteries. Metallic Li and solid-state electrolytes are currently in vogue, and they fit the bill in terms of non-Li-ion battery chemistries. The intense work worldwide, both commercially and academically, on Li and solid-state is hyper-competitive. It is the goal of this specialty section within *Frontiers in Batteries and Electrochemistry* to capture this intensity while it develops and matures with new ideas. However, a practical balanced statistical connection must be provided, with results and findings that are impartial between performance reality and hyperbole. The roadmap of solid-state and metallic lithium is fraught with decision-making processes between chemistries, architectural designs, and careful control of materials' properties, particularly regarding challenges in solid-solid (and-solid) interfaces. We need to ensure the validity of performance metrics in a transparent manner with scientific data and rigor to make claims. This specialty section will demand this.

The above systems all require supporting data and results which would be provided by the following methods: 1) advanced characterization tools such as a) cryo-TEM/SEM, b) synchrotron data, and c) imaging and computer-aided battery and particle visualization/transformation amongst others; 2) electrochemical analysis at the utmost detail, ranging from single particles to advancements in testing and battery formation protocols as well as improved measurement methods that link the chemistry to the electrochemistry, and their mechanisms; 3) modeling at multi-scales, and that which includes the latest in artificial intelligence and machine learning methods; 4) "*operando*" methods of interrogation at all levels of length and chemical specificity; and 5) combinatorial and/or high-throughput approaches to cover vast synthetic material phase spaces and electrolyte playgrounds in non-Li-ion battery chemistries in a short amount of time.

Technologies for the section "Next-Generation Batteries and Technologies" must handle, for example, electric aviation, which, at the very least would require: 1) >300 Wh/kg energy density, 2) >2 kW/kg specific power, 3) a recharge rate of 4C, 4) > 1,000 cycles (1C/1C rate at 80% DOD), and 5) a wide operating temperature range of −17°C to +70°C. These demands certainly would require Li metal or high Si anodes and much higher performance characteristics beyond the ability of traditional graphite anodes used in current day Li-ion batteries.

Lithium-air ($O_2$) batteries also present an unprecedented leap in theoretical energy densities, approaching that of petroleum products. Yet their development is still very much in the nascent or early scientific understandings stages. We will welcome such papers in this specialty topic. Particularly interesting are papers on new materials, electrolytes, and catalysts for electrochemical operation. Since such work is so novel and sometimes exploratory, we would be happy to accept great hypothesis papers to entice readers into new ideas on this (electro)chemistry.

In short, the "Next-Generation Batteries and Technologies" section represents an outlet for more future battery concepts and results that are non-Li-ion based. The section will feature, capture, and publish high-quality papers focused on cutting-edge results that will lead the field to new understandings in the recognized area of "Beyond Li-ion" batteries. It is the aim of this section to collect and disseminate both fundamental and applied ideas and research topics in all next-generation areas of batteries and technologies dedicated to advancing electrochemistry principles, tenets, and deep knowledge. Topics are open, but novelty and ground-breaking work is courted.

## Author contributions

The author confirms being the sole contributor of this work and has approved it for publication.

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## Conflict of interest

The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

## Publisher's note