Lithium-Ion Batteries: Latest Advances and Prospects

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batteries

Editorial

Lithium-Ion Batteries: Latest Advances and Prospects

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The anthropogenic release of greenhouse gases, especially carbon dioxide (CO_2), has resulted in a notable climate change and an increase in global average temperature since the mid-20th century [1,2]. To arrive at the margin of a 2 °C global temperature rise, it is essential to design and execute a multiscale comprehensive action plan to effectively mitigate climate change before its impacts overwhelm our ability to manage the situation [3–5]. Electrochemistry is a powerful tool for designing diverse CO_2 mitigation approaches that can effectively help prevent dangerous anthropogenic interference with the climate system. Several implementations of electrochemical systems are being considered within the electrochemistry and climate change framework. Besides emerging tasks such as CO_2 capture [6–8] and conversion [9–11], electrochemical systems are mainly being developed to help integrate renewable energy into electricity systems, through developing electrochemical energy storage systems such as batteries. Batteries are currently being developed to power an increasingly wide range of applications, including electrification of transportation [12,13] and grid-scale energy storage [14,15]. Large-scale developments and implementations of batteries offer sustainable energy supply based on renewables, which is a major step toward reducing CO_2 emissions associated with the energy sector and ultimately assisting in climate change mitigation.

Among the developed batteries, lithium-ion batteries (LIBs) have received the most attention, and have become increasingly important in recent years. Compared with other batteries, LIBs offer high energy density, high discharge power, high coulombic efficiencies, and long service life [16–18]. These characteristics have facilitated a remarkable advance of LIBs in many frontiers, including electric vehicles, portable and flexible electronics, and stationary applications. Since the field of LIBs is advancing rapidly and attracting an increasing number of researchers, it is necessary to often provide the community with the latest updates. Therefore, this Special Issue was designed to focus on updating the electrochemical community with the latest advances and prospects on various aspects of LIBs. Researchers were invited to submit their original research as well as review/perspective articles for publication in the Special Issue "Lithium-Ion Batteries: Latest Advances and Prospects".

In response to this call, twelve research papers [19–30] and one case report [31] were thoroughly peer-reviewed and published. The published research papers covered advances in several fronts of the technology, including detailed fundamental studies of the electrochemical cell and investigations to better improve parameters related to battery packs. In the domain of fundamental studies, various components of the electrochemical cell, including electrodes and electrolyte, were investigated. In this context, a lightweight dense polymer–carbon composite-based current collector foil for applications in LIB was developed and evaluated in comparison to the state-of-the-art aluminum foil collector [19]. It was found that the resistance of the developed electrode based on this current collector to be by a factor of five lower compared to the aluminum-based collector, which was attributed to the low contact resistance between the proposed current collector and the other elements of the electrode. In addition, due to a 50% lower material density, the developed lightweight current collector offers the possibility to significantly decrease the mass loading of the electrode, which can be of special interest for bipolar battery architectures. In another study [20], the lithium intercalation dynamics in a cathode electrode with particles of distributed size was studied using the phase-field model, aiming to better understand the effect of this particle size distribution on the LIBs' dynamic performance.

To advance the electrolyte-related research, a first principle-based modeling framework was developed to identify the physical manifestation that electrolyte degradation has on the battery and the response observed in the terminal voltage [21]. The developed framework relates the different kinds of side reactions in the electrolyte to the material properties affected due to these side reactions—these material property changes directly impact the electrochemical reactions, and ultimately the voltage across the terminals of the battery.

Internal resistance is one of the important parameters in LIBs, which requires developing precise experimental procedures and/or theoretical frameworks to accurately evaluate this parameter. In this context, two different methods were investigated in the research paper published in this Special Issue: electrochemical impedance spectroscopy (EIS) and parameter estimation based on equivalent circuit model (ECM) [22]. It was found that unlike the conventional parameter estimation method that yields a different value than EIS, internal resistances estimated based on ECM match the values obtained from EIS. The proposed methods will be supplementary in tracking the internal resistance properly which can improve the accuracy of battery performance prediction.

An experimental investigation was performed to evaluate the effect of the current rate and prior cycling on the coulombic efficiency of LIBs [23]. The determination of coulombic efficiency of LIBs can contribute to comprehend better their degradation behavior. Therefore, a detailed understanding of the effect of these parameters would be beneficial to further optimize the cell charge/discharge procedures.

Experiments were performed at high temperatures to provide better insights regarding battery performance at elevated temperatures. In this context, advanced in-operando measurement techniques such as fast impedance spectroscopy and ultrasonic waves as well as strain-gauges were employed to evaluate the cell performance at these temperatures [24]. These methods have the potential to be integrated into the battery management system in the future, making it possible to achieve higher battery safety even under the most demanding operating conditions. In addition, comprehensive hazard analysis of failing LIBs used in electric vehicles was evaluated experimentally at elevated temperatures [25]. In this investigation, several hazard-relevant parameters were quantified, including the temperature response of the cell, the maximum reached cell surface temperature, the amount of produced vent gas, the gas venting rate, the composition of the produced gases, and the size and composition of the produced particles. The results are valuable for all who deal with batteries, including firefighters, battery pack designers, and cell recyclers.

The effect of cell manufacturing parameters was also investigated on the performance of the produced LIBs. For example, a theoretical framework was developed to highlight the considerable impact of electrode porosity, electrode internal void volume, cell capacity, and capacity ratio that result from electrode coating and calendering tolerance (as the manufacturing parameters) on the cell-to-cell and lot-to-lot performance variation [26]. In another study published in this Special Issue, the impact of manufacturing parameters in laser cutting, which is a promising technology for the singulation of conventional and advanced electrodes for LIBs, was investigated [27]. In specifics, it was shown how cutting edge characteristics affect electrochemical performance. These types of information would be beneficial to manufacture better LIBs.

In addition to improving individual LIB cells, several researches were focused on strategies to obtain better battery packs. Every single cell in the battery pack needs a contact for its cell terminals, which raises the necessity of an automated contacting process with low joint resistances to reduce the energy loss in the cell transitions. A capable joining process suitable for highly electrically conductive materials like copper or aluminum is laser beam welding. In the research paper published in this Special Issue, a theoretical examination of the joint resistance and a simulation of the current flow dependent on the contacting weld's position in an overlap configuration was performed [28]. This investigation highlighted the influence of the shape and position of the weld seams as well as the laser welding parameters, and how these parameters can be leveraged to further reduce the cell-to-cell joint resistances.

For LIB packs, it is necessary to understand how to best replace poorly performing cells to extend the lifetime of the entire battery pack. In a comprehensive investigation [29], cell replacement strategies were studied considering two scenarios: early life failure, where one cell in a pack fails prematurely, and building a pack from used cells for less demanding applications. Early life failure replacement found that a new cell can perform adequately within a pack of moderately aged cells. The second scenario for the reuse of lithium-ion battery packs examines the problem of assembling a pack for less-demanding applications from a set of aged cells, which exhibit more variation in capacity and impedance than their new counterparts. The cells used in the aging comparison part of the study were deeply discharged, recovered, assembled in a new pack, and cycled. The criteria for selecting the aged cells for building a secondary pack were discussed in the paper and the performance and coulombic efficiency of the secondary pack were compared to the pack built from new cells and the repaired pack. The results showed that the pack that employed aged cells performed well, but its efficiency was reduced.

The cooling system of LIB packs used in electric vehicles was also investigated in the Special Issue. Thermal management systems of LIBs play an important role as the performance and lifespan of the batteries are affected by the temperature. A detailed study published in this Special Issue proposed a framework to establish equivalent circuit models that can reproduce the multi-physics phenomenon of Li-ion battery packs, which includes liquid cooling systems with a unified method. The developed equivalent circuit models were found to be very accurate and computationally cost-effective [30].

Besides the detailed research papers, one case report on the future portable LIB recycling challenges in Poland was published in this Special Issue [31]. This case report presents the market of portable LIBs in the European Union (EU) with particular emphasis on the stream of used cells in Poland by 2030. The report also draws attention to the fact that, despite a decade of efforts in Poland, it has not been possible to create an effective management system for waste batteries and accumulators that would include waste management, waste disposal, and component recovery technology for reuse. This report highlights the critical role of recycling strategies and challenges that need to be investigated to effectively deal with used LIBs.

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