

## Editorial

# Lithium-Ion Batteries Aging Mechanisms

Mauro Francesco Sgroi 

Centro Ricerche FIAT S.C.p.A., Strada Torino 50, 10043 Orbassano, TO, Italy; mauro.sgroi@crf.it.com

Lithium batteries (including lithium-ion, lithium-sulfur and lithium-air cells) are considered a technology enabling industrial sectors, including electrified vehicles, consumer electronics and stationary energy storage. Many research efforts have recently been devoted to the development of new materials capable of improving the performances of this type of electrochemical energy storage device [1–5]. The materials and the construction of the Li-ion cell determine, beyond the capacity, power and energy of the system, the calendar and life cycle. The durability of the cell is a key performance parameter to guarantee the penetration of energy storage systems (ESSs) in the market based on lithium batteries. Understanding the chemical and physical mechanisms affecting the cell materials and determining the degradation of the performance are the first steps to develop more reliable and durable systems. Moreover, monitoring the battery during its life through different type of sensors, in order to determine the state of health (SOH), and adopting self-healing materials are becoming the most applied solutions to improve the reliability and durability of Li-ion batteries.

In this Special Issue, we were looking for contributions helping to:

- Understand aging mechanisms through in situ and ex situ postmortem chemical analysis of cell components;
- Simulate the degradation of materials through multi-scale modeling;
- Develop new in situ and online sensing principles and approaches to monitor the degradation phenomena;
- Implement new accelerated aging protocols and data treatment techniques (e.g., machine learning);
- Improve the control strategies of the ESS to prolong the lifetime of the lithium cells;
- Develop new self-healing materials able to recover the original functionality after damage;
- Determine the impact of the aging on the safety of the ESS.

Topics of interest included, but were not limited to:

- Chemical analysis of materials and postmortem analysis;
- Innovative accelerated protocols for battery aging;
- Aging multiscale modeling;
- ESS state-of-health (SOH) estimation;
- Sensors for in situ and online cell monitoring;
- Self-healing functionalities;
- Influence of aging on cost and environmental analyses of ESSs;
- Control logics of ESS.

In response to this call for papers, six research articles [6–11] have been published. Frankerberger et al. [6] used Electrochemical Impedance Spectroscopy (EIS) and Neutron Depth Profiling (NDP) to study the impact of the lamination process on the formation of the Solid Electrolyte Interface (SEI) graphite anodes. Their main conclusion is that lamination reduces capacity fading during formation and cycling and correlates with a significant reduction in surface resistance growth. The charging process of Li-ion batteries has a great influence on aging and the deterioration of safety. Gewald and Bednorz [7] performed an experimental cycling campaign on commercial cells integrating a silicon/graphite anode and a nickel-rich cathode. Different charging rates and temperatures were explored, and the



**Citation:** Sgroi, M.F. Lithium-Ion Batteries Aging Mechanisms. *Batteries* **2022**, *8*, 205. <https://doi.org/10.3390/batteries8110205>

Received: 29 September 2022

Accepted: 1 October 2022

Published: 1 November 2022

**Publisher's Note:** MDPI stays neutral with regard to jurisdictional claims in published maps and institutional affiliations.



**Copyright:** © 2022 by the author. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

lithium-plating phenomenon was detected using a stripping technique. Another important research topic is represented by the accurate mathematical modeling of the aging of Li-ion cells. These models should be accurate enough to correctly reproduce the capacity fade but computationally fast enough to be implemented on an electronic control board of the battery-management system. Al-Gabalawy et al. implemented, using Matlab, a simplified physical–chemical model based on the single-particle approximation [8]. The understanding of battery aging phenomena is based on the development of robust and reliable electrochemical characterization techniques: Krupp et al. developed a methodology, based on incremental capacity analysis (ICA), to evaluate the state of health (SOH) of battery modules integrating lithium iron phosphate (LFP) cells connected in series [9]. The lifetime of a battery is determined by cycle and calendar aging. The latter significantly influences the expected working life of the battery package since in passenger car applications, the greatest amount of time is passed in parking conditions. Werner et al. [10] studied the empirical correlation between storage conditions and capacity fade, and they concluded that a large impact of the storage state of charge (SOC) at 100% is evident, whereas the influence is small below 80%. Moreover, instead of the commonly applied square root of the time function used to empirically simulate the capacity fade, their results agree well with an exponential function.

Finally, in situ and in operando chemical–physical characterization techniques are fundamental to understand the processes occurring in complex systems such as Li-ion cells. Möller et al. [11] used a 3 MeV proton-based ion beam analysis to study all-solid-state Li battery materials. Characteristic X-ray and gamma-ray emission analyses allowed them to visualize the migration of lithium upon charging and quantify the lithium concentration in cathode materials as a function of the state of charge and state of health.

In conclusion, the research articles published in this Special Issue were devoted to the most relevant topics associated to the study of aging phenomena in Li-ion cells and greatly contribute to the advancement of knowledge in this technologically relevant field.

**Funding:** This research received no external funding.

**Acknowledgments:** I would like to thank all people involved in this Special Issue: the authors for their very valuable contributions, and the reviewers for their availability and efforts in analyzing the relevance and quality of the papers that were submitted. I am also very grateful to MDPI for inviting me to be Guest Editor of this Special Issue and the MDPI’s editorial team for their proactiveness and support. Given the success of this Special Issue, we decided to open a second Special Issue entitled “Lithium-Ion Batteries Aging Mechanisms II”: [https://www.mdpi.com/journal/batteries/special\\_issues/Lithium\\_Ion\\_Batteries\\_Aging\\_Mechanisms\\_2](https://www.mdpi.com/journal/batteries/special_issues/Lithium_Ion_Batteries_Aging_Mechanisms_2) (accessed on 12 August 2022).

**Conflicts of Interest:** The author declares no conflict of interest.

## Abbreviations

The following abbreviations are used in this manuscript:

MDPI	Multidisciplinary Digital Publishing Institute
EES	Energy Storage Systems
SOH	State of Health

## References

1. Ahniyaz, A.; de Meatza, I.; Kvasha, A.; Garcia-Calvo, O.; Ahmed, I.; Sgroi, M.F.; Giuliano, M.; Dotoli, M.; Dumitrescu, M.A.; Jahn, M.; et al. Progress in solid-state high voltage lithium-ion battery electrolytes. *Adv. Appl. Energy* **2021**, *4*, 100070. [[CrossRef](#)]
2. Kwon, N.H.; Mouck-Makanda, D.; Fromm, K.M. A Review: Carbon Additives in LiMnPO<sub>4</sub>- and LiCoO<sub>2</sub>-Based Cathode Composites for Lithium Ion Batteries. *Batteries* **2018**, *4*, 50. [[CrossRef](#)]
3. Mauger, A.; Julien, C.M. Olivine Positive Electrodes for Li-Ion Batteries: Status and Perspectives. *Batteries* **2018**, *4*, 39. [[CrossRef](#)]
4. Chen, Z.; Zhang, W.; Yang, Z. A review on cathode materials for advanced lithium ion batteries: Microstructure designs and performance regulations. *Nanotechnology* **2019**, *31*, 012001. [[CrossRef](#)] [[PubMed](#)]
5. Nzereogu, P.; Omah, A.; Ezema, F.; Iwuoha, E.; Nwanya, A. Anode materials for lithium-ion batteries: A review. *Appl. Surf. Sci. Adv.* **2022**, *9*, 100233. [[CrossRef](#)]

6. Frankenberger, M.; Trunk, M.; Seidlmaier, S.; Dinter, A.; Dittloff, J.; Werner, L.; Gernhäuser, R.; Revay, Z.; Märkisch, B.; Gilles, R.; et al. SEI Growth Impacts of Lamination, Formation and Cycling in Lithium Ion Batteries. *Batteries* **2020**, *6*, 21. [[CrossRef](#)]
7. Bednorz, R.; Gewald, T. Investigation of the Effects of Charging Processes on Lithium-Ion Cells with SiC Anodes at Low Temperatures. *Batteries* **2020**, *6*, 34. [[CrossRef](#)]
8. Al-Gabalawy, M.; Hosny, N.S.; Hussien, S.A. Lithium-Ion Battery Modeling Including Degradation Based on Single-Particle Approximations. *Batteries* **2020**, *6*, 37. [[CrossRef](#)]
9. Krupp, A.; Ferg, E.; Schuldt, F.; Derendorf, K.; Agert, C. Incremental Capacity Analysis as a State of Health Estimation Method for Lithium-Ion Battery Modules with Series-Connected Cells. *Batteries* **2021**, *7*, 2. [[CrossRef](#)]
10. Werner, D.; Paarmann, S.; Wetzel, T. Calendar Aging of Li-Ion Cells—Experimental Investigation and Empirical Correlation. *Batteries* **2021**, *7*, 28. [[CrossRef](#)]
11. Möller, S.; Satoh, T.; Ishii, Y.; Teßmer, B.; Guerdelli, R.; Kamiya, T.; Fujita, K.; Suzuki, K.; Kato, Y.; Wiemhöfer, H.D.; et al. Absolute Local Quantification of Li as Function of State-of-Charge in All-Solid-State Li Batteries via 2D MeV Ion-Beam Analysis. *Batteries* **2021**, *7*, 41. [[CrossRef](#)]