

<https://doi.org/10.1038/s44172-025-00572-6>

Battery management systems for vehicle electrification

Check for updates

The use of electric vehicles contributes to sustainability efforts by reducing our reliance on fossil fuels and improving air quality.

Communications Engineering is delighted to present its first complete Research Collection on the topic of Battery Management Systems for Vehicle Electrification; you can read all the content here: <https://www.nature.com/collections/hfdifjhbha>.

Electric Vehicle (EV) sales continue to grow across the world. According to the International Energy Agency, more than 17 million were sold in 2024. Nearly half of new car sales in the huge Chinese market were EVs, while in Norway, around 90% electrification was achieved¹. Battery management systems are critical components of EVs, monitoring and responding to battery voltage, current, temperature, and other signals in order to optimise battery performance. Below, we outline some key areas of research exploration and describe how the papers in our collection have contributed.

Battery states

Improving our understanding and measurement of key cell parameters is critical for optimising performance. There are exciting opportunities for enhancing the traditional measurements of voltage, current and temperature, with new sensor types. For instance, Gu et al.² demonstrated how cell strain measurements can help provide additional insights towards a quantitative estimation of state-of-safety. Tracking of these states will become more important in coming years due to mandates such as the battery passport, which is highlighted in the Commentary from Bülow et al.³. The commentary reflects on how state-of-health and remaining useful lifetime can be practically tracked in real-world automotive applications. This is a sentiment shared by others. For example, Lanubile et al.⁴ leveraged domain knowledge-guided machine learning techniques towards practical state-of-health estimation, as

well as Zhang et al.⁵, who demonstrated a data-driven capacity estimation approach using fragmented charge data. Of course, capacity is not the only metric of interest and the community should also develop techniques for extracting other complementary states. This is exemplified by the work of Blömeke et al.⁶ who explored the feasibility of using balancing resistors already in place in battery management systems as a tool to stimulate cells for in situ impedance tracking, useful for the estimation of state-of-available-power. Finally, practical state-estimation is still hindered by complex phenomena such as voltage hysteresis. Jahn et al.⁷ proposed a probability-distributed equivalent circuit to capture this effect, towards more accurate state estimation.

Impact of inhomogeneities

Exploring localised cell effects. A current trend in lithium-ion batteries is the increase in individual cell capacity and as such we cannot assume homogeneous behaviour. The importance of localised effects on how cells might ultimately degrade was highlighted in several contributions. Li et al.⁸ reported a thermally coupled and distributed model showing that thermal gradients of only 3 °C can result in sufficient positive feedback to accelerate degradation by 300%. Lin et al.⁹ also reported non-uniform temperature distributions, the extent to which they stressed is influenced by underlying material properties such as solid-phase diffusion.

Scaling up to packs. Scaling up to practical packs, temperature remains a key consideration alongside configuration. For instance, He et al.¹⁰ explored how electrical connection topologies in a pack could be optimised to minimise the accelerated cell ageing caused by thermal gradients. Similarly, Naylor Marlow et al.¹¹ explored the impact of thermal gradients in parallel connected cells, identifying convergent and divergent modes of cell degradation trajectory, highlighting the importance of the cathode impedance. The practical challenges with battery packs are compounded by the volume of potential failure points, which has motivated work in pack failure detection across modalities.

This is exemplified by the work of Naguib et al.¹² who reported an integrated physics and deep neural network-based model to detect thermal faults in packs and also the work of Lambert et al.¹³, who reported a method to detect faults in complex large battery packs using current distributions.

Emerging tools

Looking to the future, two Perspective Articles in the Collection explore emerging tools of value to this field. Berecibar and Zeng¹⁴ focused on the variety of different sensors used for monitoring battery systems, allowing for the generation of new data streams, also bringing in physics-guided methods. Meanwhile, Manashita Borah and colleagues¹⁵ deeply explored the strategies for integrating physics and machine learning in future battery management systems, allowing the extraction of more detailed insights and new opportunities for state estimation and system optimization in the future.

Outlook

EVs will undoubtedly dominate the future of the automotive world. But there is still scope for performance improvements. There is a need for new cell formats with greater energy density, longer lifetimes, cost efficiency, and improved safety. Combining new understanding with technological innovation will lead the way to these much-needed developments. We hope that the ideas presented in our Collection will be stimulating for those working in the field, towards these goals.

Published online: 21 January 2026

References

1. IEA, Global EV Outlook 2025, IEA, Paris (2025). <https://www.iea.org/reports/global-ev-outlook-2025/trends-in-electric-car-markets-2>.
2. Gu, X. et al. Early warning of thermal runaway based on state of safety for lithium-ion batteries. *Commun. Eng.* **4**, 106 (2025).
3. von Bülow, F., Heinrich, F. & Paxton, W. A. The future of battery data and the state of health of lithium-ion batteries in automotive applications. *Commun. Eng.* **3**, 173 (2024).

4. Lanubile, A. et al. Domain knowledge-guided machine learning framework for state of health estimation in Lithium-ion batteries. *Commun. Eng.* **3**, 168 (2024).
5. Zhang, Z. et al. Data-driven available capacity estimation of lithium-ion batteries based on fragmented charge capacity. *Commun. Eng.* **4**, 32 (2025).
6. Blömeke, A. et al. Balancing resistor-based online electrochemical impedance spectroscopy in battery systems: opportunities and limitations. *Commun. Eng.* **3**, 62 (2024).
7. Jahn, L. et al. A physically motivated voltage hysteresis model for lithium-ion batteries using a probability distributed equivalent circuit. *Commun. Eng.* **3**, 74 (2024).
8. Li, S. et al. Effect of thermal gradients on inhomogeneous degradation in lithium-ion batteries. *Commun. Eng.* **2**, 74 (2023).
9. Lin, J. et al. Multiscale coupling of surface temperature with solid diffusion in large lithium-ion pouch cells. *Commun. Eng.* **1**, 1 (2022).
10. He, H. et al. Numerical investigation of module-level inhomogeneous ageing in lithium-ion batteries from temperature gradients and electrical connection topologies. *Commun. Eng.* **3**, 89 (2024).
11. Naylor Marlow, M., Chen, J. & Wu, B. Degradation in parallel-connected lithium-ion battery packs under thermal gradients. *Commun. Eng.* **3**, 2 (2024).
12. Naguib, M. et al. Thermal fault detection of lithium-ion battery packs through an integrated physics and deep neural network based model. *Commun. Eng.* **4**, 79 (2025).
13. Lambert, P. et al. Detecting faulty lithium-ion cells in large-scale parallel battery packs using current distributions. *Commun. Eng.* <https://doi.org/10.1038/s44172-025-00543-x> (2025).
14. Zeng, X. & Berecibar, M. Emerging sensor technologies and physics-guided methods for monitoring automotive lithium-based batteries. *Commun. Eng.* **4**, 44 (2025).
15. Borah, M. et al. Synergizing physics and machine learning for advanced battery management. *Commun. Eng.* **3**, 134 (2024).

Open Access This article is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License, which permits any non-commercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if you modified the licensed material. You do not have permission under this licence to share adapted material derived from this article or parts of it. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by-nc-nd/4.0/>.

© Springer Nature Limited 2026