INSIGHT SERIES

FROM EXPERTISE TO IMPACT

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# Lithium-Metal and Anode-Free Cells: From Cell Potential to System Reality

## Abstract

*Electric aviation depends on batteries that deliver very high energy density without compromising power, safety, or system integration. A review of FEV's battery-cell database, covering more than 1,600 cells across different chemistries, shows that the ultra-high-energy region is increasingly occupied by lithium-metal and anode-free technologies. In this article, FEV summarises benchmarking results from a high-energy anode-free prototype cell selected for aviation-relevant assessment. The cell demonstrated specific energy above 410 Wh/kg and strong discharge capability with lower self-heating than a conventional NMC-graphite reference cell. Thermal-abuse testing also indicated promising stability, with no thermal runaway observed up to 190 degrees C under the applied ARC Heat-Wait-Seek procedure. At the same time, cycling stability and cell swelling remain key development challenges that must be solved at module and pack level. The results illustrate the central message of HyLiST: exceptional cell performance must be translated into manufacturable, safe, and durable battery systems before high-energy technologies can become a practical reality for electric and hybrid-electric aircraft.*

## Every kilogram has a flight consequence

**In aviation, battery mass is not simply an inconvenience**; it directly affects payload, range, mission capability, and ultimately the feasibility of an aircraft concept. **Battery cells are therefore a key enabling technology for electric and hybrid-electric aircraft**. Their energy density largely determines whether an aircraft can meet its range and payload targets while still carrying the power reserve required for take-off, climb, diversion, and safe operation.

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Although electric propulsion and aircraft integration are advancing quickly, battery technology remains one of the primary limitations. Many future aviation concepts require cell-level specific energies above 400 Wh/kg while also meeting demanding requirements for power capability, safety, thermal management, lifetime, and certification. **The relevant question is whether high-energy cell concepts can be transformed into reliable battery systems**.

## Why the next step is needed

Conventional lithium-ion cells have enabled the growth of electric mobility, but graphite-based anodes are approaching their practical energy-density limits. Analysis of FEV's cell database, containing **more than 1,600 battery cells** across various chemistries, shows that the **ultra-high-energy region is dominated by lithium-metal and anode-free technologies**. This technology landscape is the starting point for the benchmarking work described in this article.

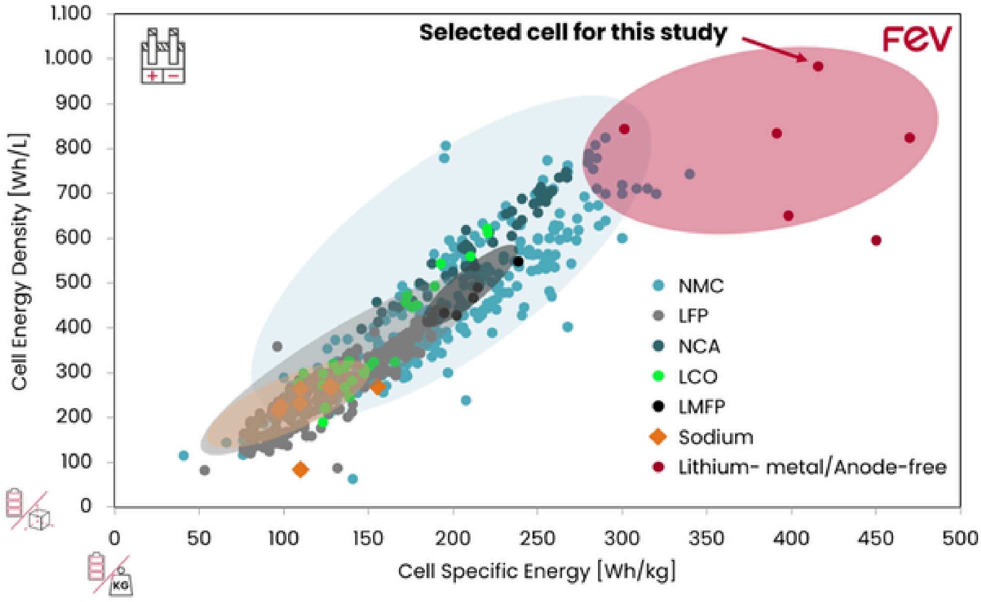


*Figure 1 - Energy-density distribution of battery cell technologies in the FEV database, highlighting lithium-metal and anode-free cells. Note: replace the editorial visual with the original FEV database figure if available before publication.*

## The change happens at the anode

In a conventional NMC-graphite cell, lithium is initially stored in the cathode. During charging, lithium moves from the cathode into the graphite anode; during discharging, lithium moves back to the cathode. This architecture is mature and robust, but **graphite primarily acts as a host material** and adds significant mass and volume.

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**Lithium-metal and anode-free cells take a different approach**. Instead of storing lithium in a thick graphite host, lithium is stored as metallic lithium or is plated directly onto a current collector during charging. This **increases the amount of charge that can be stored per unit mass and volume of the anode**. The result is significantly **higher cell-level energy density**, which makes these technologies increasingly attractive for aviation applications.

## A cell with aviation-relevant numbers

One of the **highest-energy prototype cells** in the FEV Cell Database was selected for benchmarking. The **commercial 50 Ah semi-solid-state anode-free NMC cell** combines a practical format for module and pack development with **more than 410 Wh/kg and more than 950 Wh/l**.

For comparison, **a conventional 150 Ah NMC-graphite EV cell with approximately 260 Wh/kg and 600 Wh/l was used as a reference**. The higher energy density of the anode-free cell makes electric and hybrid-electric aviation concepts more technically feasible while enabling meaningful module, and pack-level investigations. The results presented here are part of FEV's benchmarking, testing, and pack-development activities within the European HyLiST project.

## Test outcomes

The selected cell was assessed across performance, thermal behaviour, safety-relevant stability, cycling, and mechanical integration aspects. The central findings can be summarised as follows:

- **High energy density:** the anode-free cell exceeded 410 Wh/kg and 950 Wh/l, placing it in the technology region of interest for aviation.
- **Power capability:** discharge performance remained comparable to the automotive reference cell up to 1C, with strong capability at higher rates.
- **Lower self-heating:** at 3C discharge, the anode-free cell remained below 40 degrees C, while the EV reference cell reached approximately 55 degrees C and the test was stopped at the defined temperature limit.
- **Promising thermal stability:** under ARC Heat-Wait-Seek testing, fully charged anode-free cells showed self-heating events at approximately 128 degrees C and 165 degrees C, but no thermal runaway occurred up to 190 degrees C.
- **Development need in cycling:** the evaluated cell achieved approximately 70% capacity retention after 100 cycles, which is consistent with the manufacturer's specification but still below mature automotive lithium-ion cells.
- **New mechanical requirements**: the tested 50 Ah anode-free cell showed approximately 30% thickness increase during cycling, indicating that module designs must actively manage swelling, stack pressure, and packaging tolerance.

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## HyLiST connection: from promising cells to system reality

The HyLiST project focuses on the development of high-energy, safe, and sustainable solid-state battery concepts for demanding applications such as electric mobility and aviation. Within this framework, FEV's benchmarking activities provide a system-oriented view of emerging cell technologies.

The objective is **not only to identify high-energy cells**, but also **to understand their implications** for module architecture, thermal management, safety strategy, and pack-level feasibility.

**Lithium-metal and anode-free concepts align strongly with the project's ambition** because they can unlock the energy densities needed for next-generation battery systems. At the same time, the test results show why system development is essential. **A cell that performs well at cell level must still be integrated into a battery pack** that controls heat generation, accommodates swelling, maintains mechanical pressure, prevents propagation, and satisfies aviation-grade safety requirements.

This is where HyLiST creates value: by connecting materials innovation, cell benchmarking, pack engineering, test methodology, and scalability considerations. **The project helps translate high-energy cell potential into practical design rules for future electric and hybrid-electric aircraft battery systems**.

## Conclusion

**The FEV benchmarking results confirm that lithium-metal and anode-free technologies occupy the most promising region of the battery technology landscape for aviation**. The tested anode-free cell demonstrated aviation-relevant energy density, competitive power behaviour, reduced self-heating, and promising thermal stability under the applied abuse-test conditions.

However, the results also underline that **energy density alone is not enough**. Cycling stability, swelling behaviour, pack architecture, thermal management, and certification-oriented safety testing will determine whether these technologies can progress from cell potential to system reality. Recent progress in lithium-metal and anode-free cells suggests that the gap is narrowing.

The next decisive step is to **convert cell-level performance into safe, durable, scalable, and certifiable battery systems**. This is precisely the role of projects such as HyLiST.

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HyLiST

## About the author

*Dr. Arash Payandeh is a Technical Specialist for Battery Cells at FEV Europe GmbH, where he focuses on advanced battery cell development, technology selection, and next-generation energy storage solutions. His work includes managing battery cell development projects, supporting customers in cell technology selection and assessment, conducting material analysis and cell teardown investigations, and leading the development of advanced battery testing laboratories.*

*Prior to joining FEV, he held postdoctoral research positions at the Karlsruhe Institute of Technology (KIT) and Empa, where his research focused on solid-state batteries, cathode development, silicon anodes, and advanced solid electrolytes. He received his Ph.D. from Aarhus University, Denmark, specialising in solid-state ion conductors and energy-storage materials.*

*His current activities combine battery cell development, technology assessment, prototyping, advanced testing, and emerging battery technologies, with a strong focus on bridging innovative research concepts and industrial applications. Through European research initiatives such as HyLiST and other collaborative projects, he contributes to the development of next-generation battery technologies for sustainable mobility and high-performance energy storage systems.*

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