FEV

#84

SPECTRUM

360° battery development



AI-enabled battery digital twins P. 06

Lithium-metal cells for aviation P. 12

eDLP: Battery testing across industries P. 20

Engineering batteries for second life P. 42



Dear readers,

Engineering is becoming more connected. As products become more complex, successful development depends on bringing together data, simulation, testing, and expertise across disciplines. Few areas demonstrate this more clearly than battery development.

Performance, safety, cost, system integration, regulatory requirements, and lifecycle considerations all need to be considered together. This issue of SPECTRUM looks at how these connections are shaping the future of battery engineering.

AI-enabled digital twins provide new insights into battery condition, aging, and performance. Lithium-metal and anode-free cells offer the potential for higher specific energy in applications such as aviation. At the same time, they show that advances at cell level must be matched by the right module and pack concepts. Turning these innovations into reliable products requires more than digital development. They also need to be validated under real-world conditions.

Physical testing provides the evidence needed to validate battery systems under electrical, mechanical, thermal, and environmental loads. At the FEV eDLP in Brehna, our battery engineering and validation capabilities support these challenges across industries.

The articles also explore the technical and economic decisions behind battery systems. Design-to-value connects product architecture with cost, customer value, production, sustainability, and supply chain considerations. FEV BATT.code supports the development and comparison of scalable stationary energy storage concepts. Second-life applications and recycling show how battery and ecosystem design influence circularity and end-of-life economics.

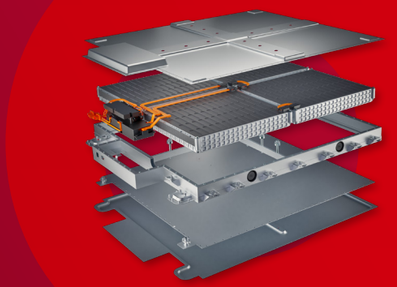
AI is also becoming an important part of engineering workflows. Our Regulation Analysis Assistant uses AI to turn complex regulatory documents into traceable engineering requirements. Like our digital twins, it is part of a controlled engineering process, not a standalone solution.

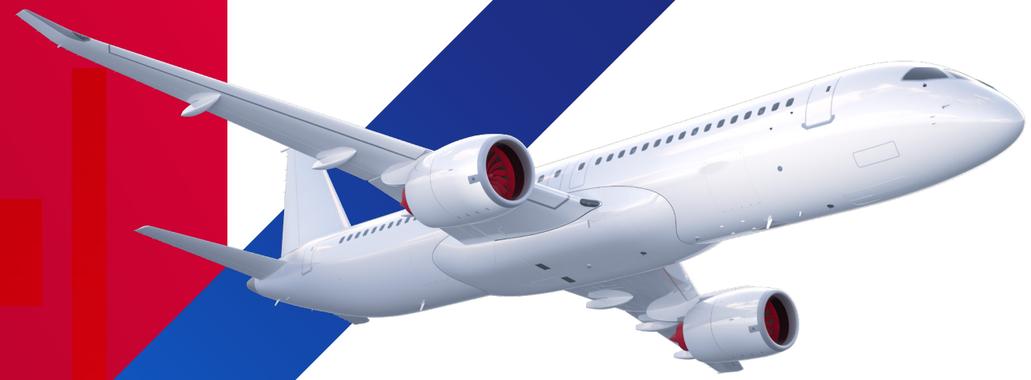
Together, these contributions highlight a simple principle: progress does not come from individual technologies alone. It comes from connecting technologies, disciplines, and expertise – from concept development and validation to operation, reuse, and recycling.

Enjoy the read!



Dr. Norbert W. Alt
Chief Operating Officer (COO) and
Executive Vice President of FEV Group





#1 AI-enabled battery digital twins for lifecycle intelligence **P. 6**

#2 Lithium-metal and anode-free cells: From cell potential to system reality **P. 12**

#3 eDLP: One battery test infrastructure – Multiple industries **P. 20**

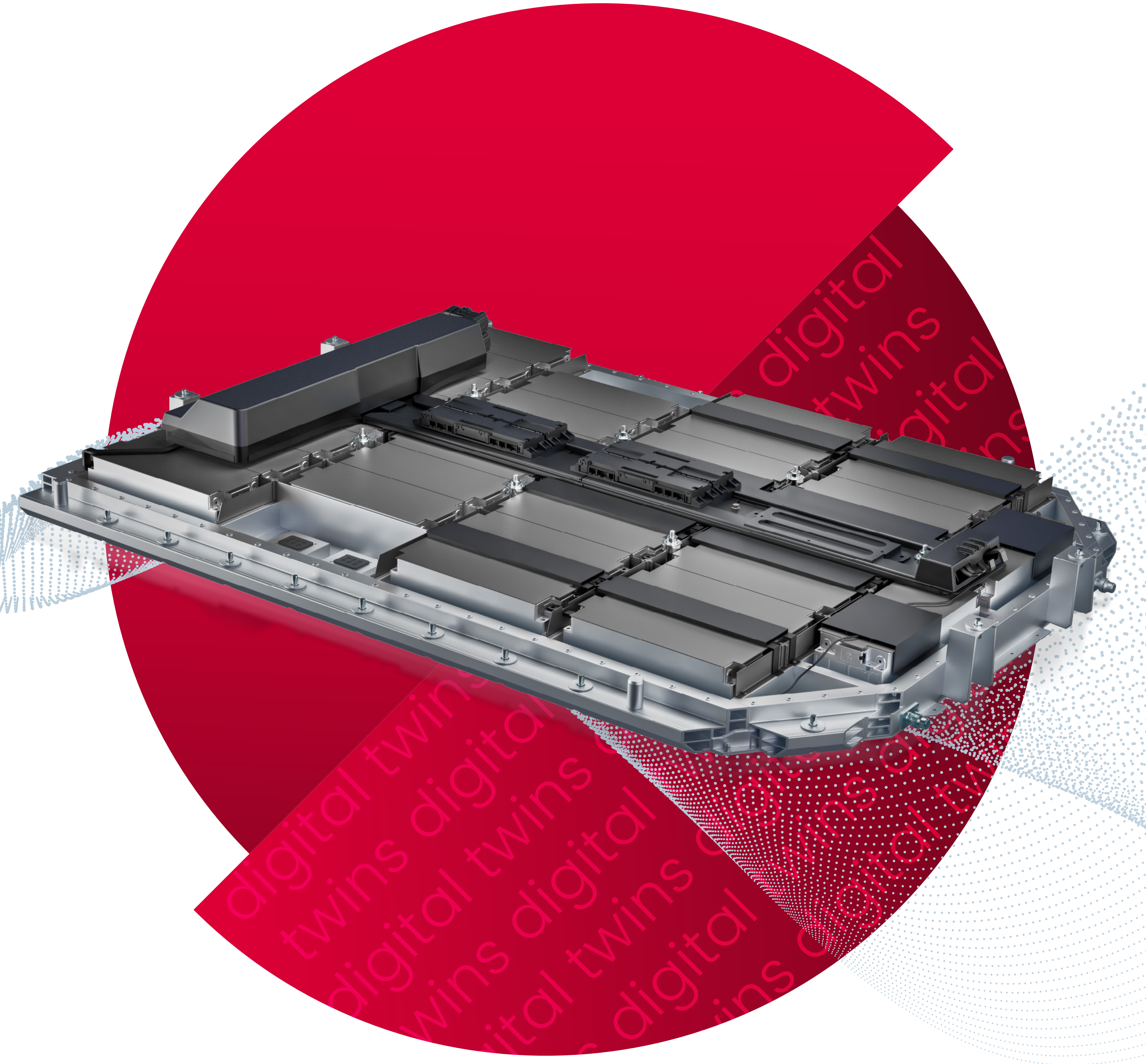
#4 Design-to-value for competitive battery development **P. 28**

#5 Concept development for scalable battery energy storage systems with BATT.code **P. 34**

#6 Beyond recycling: Engineering the second life of batteries **P. 42**

#7 Requirements at a click: How agentic AI turns norms and standards into traceable engineering requirements **P. 48**





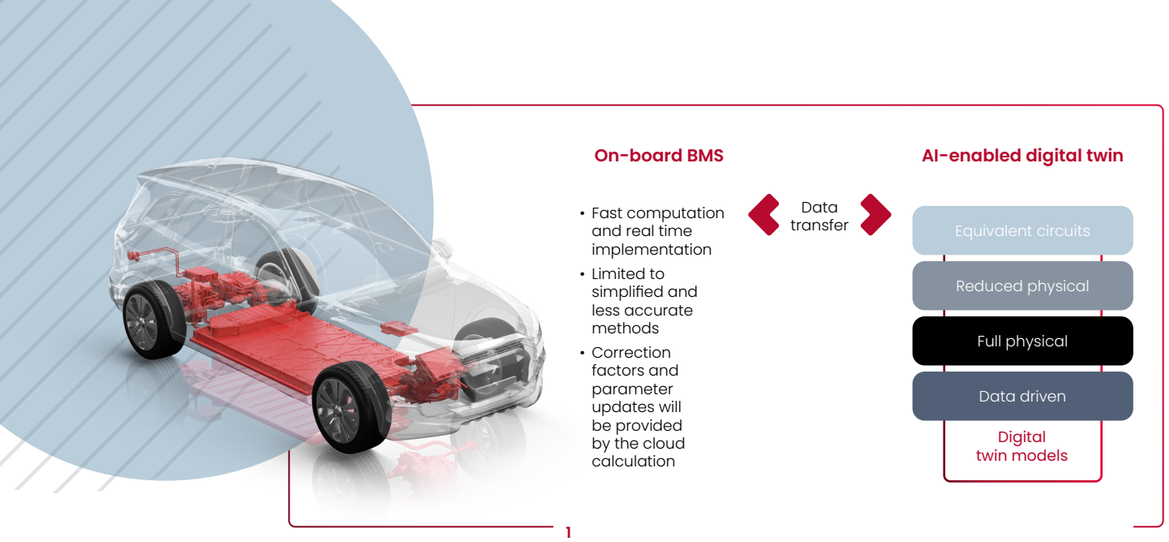
#1 AI-enabled ***battery digital twins*** for lifecycle intelligence

Digital battery twins are becoming a central building block for the next generation of battery management systems. Classical on-board battery management systems remain indispensable for safe real-time operation, but they are constrained by limited computing resources, storage capacity, and vehicle-local data history. AI-enabled digital twins extend this view by connecting vehicle data, cloud analytics, physics-based models, and machine learning into a continuously updated virtual representation of the battery system.

Despite growing battery data from development and field operation, many lifecycle decisions still lack transparency. OEMs need insight into real-world battery aging, while fleet operators require predictable availability and condition-based maintenance. Warranty exposure and residual value also depend on battery condition. The challenge is not only collecting data but translating fragmented test-bench and fleet data into reliable lifecycle intelligence.

From on-board BMS to cloud-based battery intelligence

The on-board BMS remains the safety-critical control representative in the vehicle. It monitors cell voltages, currents, temperatures, insulation, contactors, and operating limits, and it calculates key state variables such as state of charge, state of health, state of power, and remaining operating limits. These functions must be deterministic, robust, and real-time capable. For this reason, embedded BMS algorithms are typically optimized for execution on resource-constrained control units and must prioritize reliability, response time, and functional safety.



1
FEV's digital twin concept. The traditional on-board BMS implements real-time-capable functions, while the AI-enabled digital twin implements advanced analytics, diagnostics, and optimization strategies.

A cloud-based BMS complements this local control layer without replacing it. Vehicle and battery data are transferred to a secure backend, where longer data histories, fleet-wide comparisons, and computationally intensive models can be applied. This enables advanced diagnostics, degradation trend analysis, anomaly detection, model calibration, and predictive maintenance recommendations that are not feasible to the same extent on the vehicle control unit alone. This functional split is central to FEV's cloud-BMS and battery digital twin approach: fast protection and control remain in the vehicle, while advanced analytics, optimization, and predictive maintenance are executed on a scalable cloud platform.

A battery digital twin is more than a dashboard. It is a synchronized digital representation of the physical battery, continuously updated with operational data and enriched by models that describe current behavior and predict future states. AI enables this representation to learn from prototype and fleet data, identify nonlinear degradation patterns, detect deviations from expected behavior, and improve the quality of state estimation as new data become available. In industrial applications, the strongest approach is usually not purely data-driven, but hybrid: physics-based battery knowledge provides interpretability and engineering robustness, while AI adds scalability, pattern recognition, and predictive capability learned from prototype, test-bench, and fleet data.

Core applications for battery management

In practical applications, AI-enabled battery digital twins create value in three main areas: health and lifetime prediction, early fault detection, and condition-based operation and maintenance.

The first application is advanced state-of-health estimation. In real fleets, battery aging is influenced by temperature, C-rate, depth of discharge, calendar aging, charging behavior, and individual cell variation. A digital twin can evaluate charge events, normalize beginning-of-life differences, compensate for temperature effects, and derive health indicators such as capacity fade and internal resistance increase. When reliable test-bench or field data is available, AI-based health tracking gives OEMs and fleet operators a more transparent view of battery aging across vehicles, operating profiles, and usage conditions.

Remaining useful life prediction is the natural extension of SOH estimation. By combining historical load profiles, similarity analysis, degradation trajectories, and uncertainty-aware prediction models, the digital twin can forecast how long a battery is expected to remain within a defined performance or warranty corridor. This is particularly relevant where battery replacement decisions must balance technical risk, operating cost, vehicle availability, and residual value.

The second application area is early fault detection. Many critical battery issues do not start as obvious limit violations. Internal short circuits, lithium plating, contact resistance growth, local thermal anomalies, or cell imbalance often begin as small deviations in the interaction of voltage, current, temperature, SOC, and cell dispersion. AI-based anomaly detection like FEV's variational autoencoder can evaluate these multidimensional patterns across fleets and highlight deviations from expected healthy behavior before they become critical.

The third application area is predictive maintenance and operation optimization. Rather than relying on fixed service intervals or reactive diagnostics, the twin can recommend actions based on actual condition. It can optimize charging, range and route planning, cell benchmarking, replacement planning, and second-life or recycling decisions. For commercial fleets, this can increase uptime, reduce warranty exposure, improve asset utilization, and provide greater transparency regarding total cost of ownership.

FEV's portfolio perspective

FEV's digital battery twin portfolio combines BMS development experience, advanced SOX algorithms, battery system engineering, software expertise, and applied data science. It covers data requirements, ingestion and transformation pipelines, analytics engines, model development and deployment, and engineering visualizations. Its aim is to translate heterogeneous battery, vehicle, and fleet data into actionable engineering and service decisions.



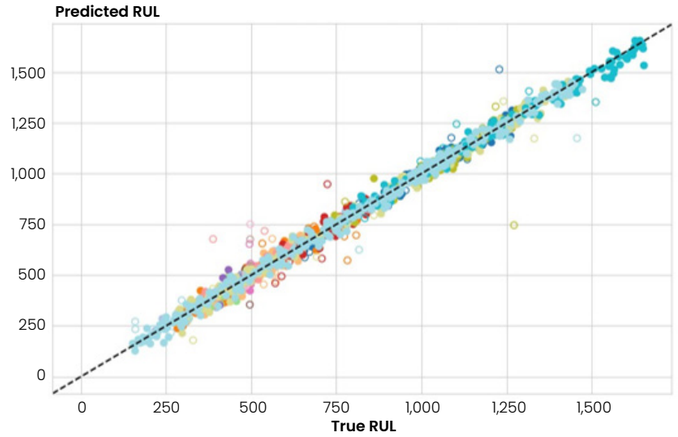
2
Selected functions of FEV's digital battery twin portfolio.

Data is the decisive enabler

Digital twin performance depends on available data. Core signals include time, current, voltage, temperature, mileage, and operating states. SOC, capacity indicators, ampere-hour counters, BMS modes, charging information, ambient temperature, and cell-level statistics improve model fidelity. Sampling rate, resolution, synchronization, missing values, and event coverage directly affect achievable accuracy.

AI-enabled digital twins use data from development models, test benches, prototypes, and vehicle fleets. Real-world data can be noisy, asynchronous, incomplete, or recorded differently across vehicle platforms. Vehicles may also differ in cell chemistry, module configuration, thermal system, software version, or calibration state. Without normalization, usage and environmental effects may be misinterpreted as aging, misuse, or faults. Data engineering is therefore a core competence: pipelines must parse, clean, align, normalize, and contextualize signals before AI models can deliver reliable outputs.

Typical FEV digital battery twin functions include SOC and SOH estimation, remaining useful life (RUL) prediction, early fault detection and diagnosis, thermal misbehavior prediction, trend analysis, fleet benchmarking, and decision-support logic for charging or maintenance. Figure 3 shows RUL prediction of FEV's digital battery twin validated with up to three years of field data from approximately 100 vehicles operated under diverse conditions. The results showed strong agreement between predicted and observed RUL trends.



3
Validation results of FEV's remaining useful life (RUL) prediction using digital battery twins and real-world vehicle fleet data.

The portfolio supports deployment from stand-alone applications to integration into customer cloud platforms. This flexibility is important because data availability, cloud infrastructure, and integration depth differ between prototype projects, fleet pilots, and industrial rollouts.

The integration of FEV's GenAISys platform further enhances AI-enabled digital battery twins by providing a generative AI interface that enables intuitive access to battery insights, diagnostics, and predictive analytics through natural-language interactions. By connecting cloud analytics, digital twin models, fleet data, and engineering knowledge, GenAISys accelerates root-cause analysis, automates reporting, and supports data-driven decision-making across the entire battery lifecycle, starting with the system development process.

Because a battery digital twin depends on complete, consistent, high-quality data, its roadmap should begin with the OEM's or fleet operator's business objectives and required data foundation. FEV can identify use cases, assess data readiness, prioritize implementation steps, and define a phased roadmap from proof of concept to scalable fleet deployment. FEV's AI capabilities include everything from data interfaces in the vehicle-to-cloud infrastructure selection and setup.

To fully exploit the value of a digital battery twin, its development should be considered early in system development, before start of production. This ensures that sensor concepts, signal availability, logging strategies, cloud interfaces, validation data, and governance processes are aligned with the intended digital twin use cases from the beginning. By clarifying these requirements early, FEV can help customers avoid costly redesigns and build digital twin capabilities on a scalable and reliable basis.

Regulation, transparency, and circular economy

Regulatory trends further strengthen the role of cloud-connected battery intelligence. Euro 7 increases the relevance of durability monitoring, while the European Battery Regulation and the digital battery passport raise expectations for lifecycle transparency, traceability, and documented battery condition. Digital twins can support these requirements by creating a consistent data basis for health assessment, usage history, diagnostics, residual value estimation, second-life qualification, and end-of-life decisions.

This lifecycle perspective also supports circular economy strategies. A battery that is accurately monitored throughout operation can be used more efficiently, serviced more selectively, and evaluated more reliably at the end of its first life. The digital twin therefore becomes an enabler not only for vehicle operation, but also for warranty handling, fleet economics, repair concepts, reuse, resale, recycling, and design for the circular economy.

Industrialization challenges

Series-capable digital twins require more than accurate algorithms. Deployment must address data governance, cybersecurity, privacy, cloud integration, model validation, monitoring, and robust updates. AI models must be explainable for engineering decisions and reliable in safety-relevant workflows, as false positives cause unnecessary service effort and false negatives compromise safety and trust. Validation must therefore cover representative driving profiles, accelerated aging data, feasible fault injections, and continuous comparison of predictions with field observations.

Model transferability is another challenge. A model trained for one cell chemistry, pack design, thermal concept, or usage profile may not transfer directly to another application. Scalable platforms therefore need modular architectures, configurable model chains, automated retraining, and clear calibration procedures. FEV combines reusable analytics modules with customer-specific adaptation to tailor algorithms to available data, target accuracy, and deployment environment.

Conclusion

AI-enabled digital twins expand battery management from real-time protection toward lifecycle-oriented intelligence. They combine on-board measurements, cloud infrastructure, physics-based models, and machine learning to assess battery condition, predict degradation, detect early faults, and support predictive maintenance. For OEMs and fleet operators, this means better transparency, improved safety, optimized operation, and more reliable decisions on service, warranty, residual value, and circular economy strategies — all of which contribute to enhanced profitability.

FEV's battery digital twin portfolio is positioned at this interface between battery engineering and data-driven intelligence. By integrating BMS know-how, cloud-based services, machine learning algorithms, hybrid models, and engineering analytics, FEV can support customers from concept and proof of concept to fleet pilot and industrial deployment. As electric vehicle batteries become increasingly connected, regulated, and value-critical, AI-enabled digital twins will become a key technology for safe, economical, and sustainable battery management.

BY
Dr. Maximilian Kloock
kloock@fev.com



#2 Lithium-metal and anode-free cells: ***From cell potential to system reality***



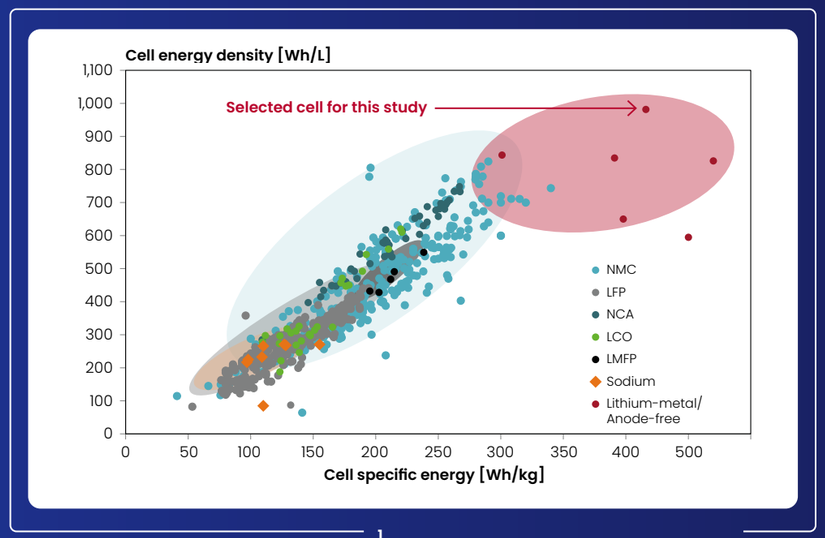
Every kilogram has a flight consequence

In aviation, battery mass is not simply an inconvenience; it directly affects payload, range, and mission capability. As a result, battery cells are a key enabling technology for electric and hybrid-electric aircraft, because their energy density largely determines whether a given aircraft concept is technically and economically feasible. While electric propulsion and aircraft integration continue to advance rapidly, battery technology remains the primary limitation. Many future aviation concepts require cell-level specific energies above 400 Wh/kg, while still meeting demanding requirements for power, safety, and lifetime.

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. An 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 cell technologies.

[**Lithium metal battery cell**]



1
Energy-density distribution of battery cell technologies in the FEV database, highlighting lithium-metal and anode-free cells.

A cell with aviation-relevant numbers

One of the highest-energy prototype cells in FEV's cell database was selected for this study, as highlighted in Figure 1. The commercial 50 Ah semi-solid-state anode-free NMC cell combines a practical format for module and pack development with >410 Wh/kg and >950 Wh/L.

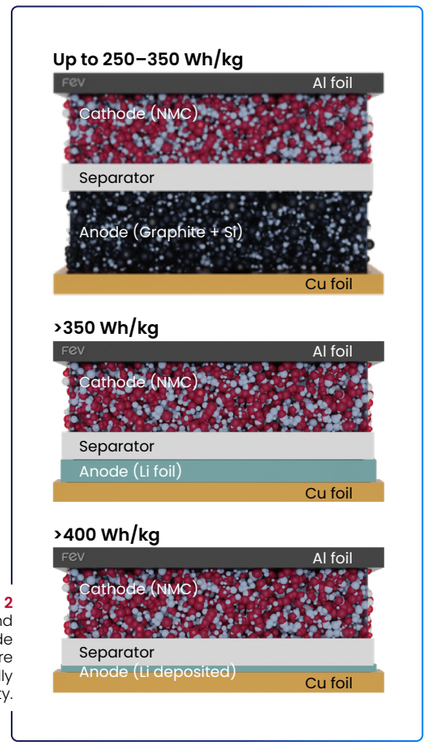
For comparison, a conventional 150 Ah NMC-graphite EV cell with approximately 260 Wh/kg and 600 Wh/L was used as a reference. The significantly higher energy density of the anode-free cell makes electric and hybrid-electric aviation concepts more technically feasible and enables meaningful module- and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

Power capability without excessive self-heating

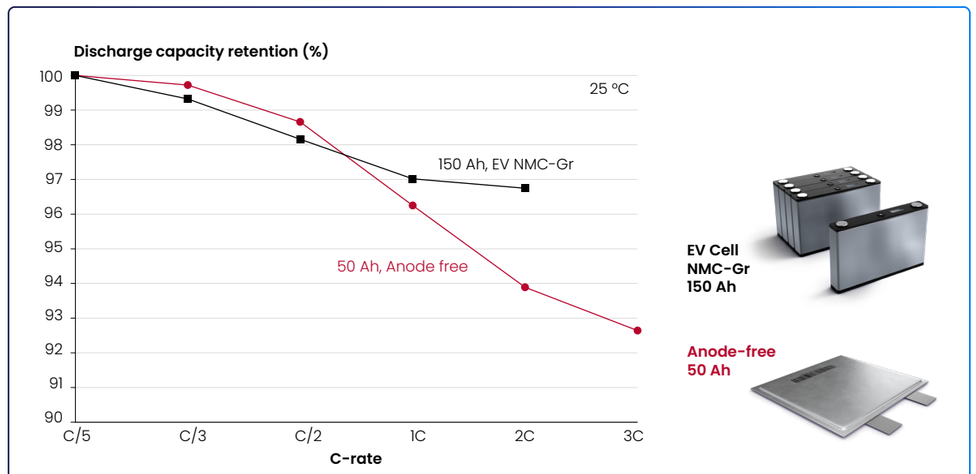
High energy density alone is not sufficient for electric aviation applications, including eVTOLs. Take-off, climb, and reserve scenarios require high discharge power while keeping thermal loads under control. Therefore, cell-level performance tests were conducted to evaluate rate capability and thermal behavior. The anode-free cell showed discharge performance comparable to the EV reference cell up to 1C and maintained strong capability at higher rates. At 3C discharge, the anode-free cell remained below 40 °C, while the EV reference cell reached approximately 55 °C, resulting in test termination at the defined temperature limit. Lower self-heating is particularly attractive for aviation battery systems, as it can reduce cooling requirements, system weight, and overall integration effort.

The change happens at the anode

In a conventional NMC-graphite cell, lithium is initially stored in the cathode. While charging, lithium moves from the cathode into the graphite anode, while during discharging it moves back to the cathode. This anode architecture is mature and robust, but the graphite primarily acts as a host material and adds significant mass and volume. 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 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, enabling significantly higher cell-level energy density and making these technologies increasingly attractive for aviation applications.



2
Comparison of graphite-silicon, lithium-metal, and anode-free cell architectures. For the same cathode capacity, lithium-metal and anode-free concepts require significantly less anode material, enabling substantially higher cell-level specific energy and energy density.



3
Discharge C-rate performance comparison of the cells.



Promising thermal stability

Safety is one of the most critical requirements for future aviation batteries. To assess thermal stability, the anode-free cell was evaluated using FEV's advanced battery safety test capabilities, including Accelerating Rate Calorimetry (ARC).

Fully charged cells were subjected to a Heat-Wait-Seek procedure, in which the temperature is increased stepwise while monitoring self-heating reactions. During testing, the anode-free cell showed self-heating events at approximately 128 °C and 165 °C, but no thermal runaway occurred up to 190 °C. Although the cell became electrically inactive after the second event, it remained structurally intact.

By comparison, the reference NMC-graphite EV cell entered thermal runaway at approximately 136 °C, resulting in cell rupture and temperatures exceeding 900 °C. These results indicate promising thermal stability for the evaluated anode-free cell technology. However, further abuse, propagation, and certification testing will be required before deployment in aviation applications.

Cycling remains part of the development story

While energy density and thermal stability are highly promising, long-term cycling performance remains one of the main development challenges for anode-free technology. The evaluated anode-free cell reached approximately 70% capacity retention after 100 cycles, in line with the manufacturer's specification. In comparison, advanced automotive lithium-ion cells typically achieve cycle lives exceeding 1,000 cycles at substantially higher remaining capacity levels.

Nevertheless, FEV's benchmarking activities indicate rapid progress in the field. More recent lithium-metal and anode-free cells already demonstrate substantially improved cycling performance while maintaining high energy density. Although further improvements are still required, the current development pace suggests that cycling stability is steadily moving closer to the requirements of future aviation applications.

Swelling changes the mechanical problem

Battery cells expand and contract during operation as lithium moves between the electrodes, a phenomenon known as cell swelling or cell breathing. For conventional EV batteries, the reversible thickness change during a charge-discharge cycle is typically <5% for graphite-based cells and around 8% for silicon-containing cells.

In contrast, the lithium in anode-free cells is repeatedly plated and stripped in the absence of a graphite host structure. As a result, the tested 50 Ah anode-free cell exhibited approximately a 30% thickness increase during cycling, creating a significant challenge for module and pack integration.

Future lithium-metal and anode-free battery systems will therefore require dedicated pack architectures that accommodate cell expansion while maintaining stack pressure, safety, and energy density.

From cell numbers to aviation packs

Testing of the 50 Ah anode-free cell demonstrated several promising characteristics. To assess how these cell-level benefits can be translated into aircraft applications, FEV's BATT.code concept-development tool was used. The tool enables a rapid transition from cell properties to module, pack, and complete system-level concepts, allowing different application scenarios to be evaluated at an early stage.

Based on requirements provided by an aviation industry partner, nine battery-system concepts were generated and assessed. The primary target application was a hybrid-electric regional aircraft requiring a battery system with 350–450 kWh installed energy, 750–1200 V operating voltage, and 800–1000 kW continuous discharge power.

To meet these requirements, a modular battery architecture was developed. The concept combines dedicated monitoring and protection of individual battery units with the flexibility to scale the system for different mission profiles. As a result, the same platform can be adapted for hybrid-electric regional aircraft, general aviation aircraft, and future eVTOL applications.

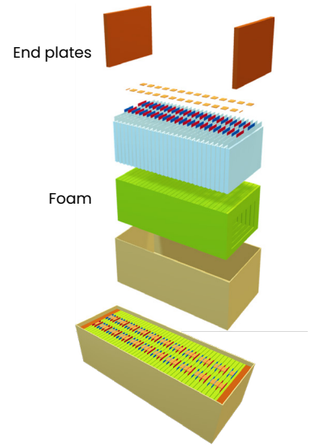
Special module design for lithium-metal and anode-free cells

Following the concept evaluation, the most promising system architecture was selected for further development. Due to the significantly higher swelling of anode-free cells, dedicated measures are required to compensate for cell expansion while minimizing the impact on pack energy density. To address this challenge, two module concepts were investigated.

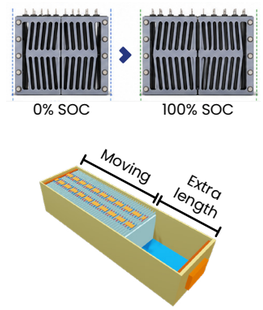
Concept A follows a conventional EV approach, using foam between adjacent cells to absorb expansion. While approximately 1.5 mm foam is sufficient for cells with up to 8% swelling, the tested anode-free cell would require roughly 8 mm foam, resulting in a significant energy-density penalty.

FEV BATT.CODE

Concept A



Concept B



4
Module concepts for anode-free battery integration. Concept A: foam-based compensation of cell swelling; Concept B: controlled cell expansion using movable components while maintaining stack pressure.

Concept B was developed specifically for high-swelling cells. Instead of absorbing expansion with foam, the cells are allowed to expand in a controlled direction while a mechanical system maintains the required stack pressure. Although more complex, this approach reduces inactive material and improves pack-level energy density.

Based on the optimization study, Concept B was selected for further development. The resulting module configuration was 2P × 21S, providing a nominal voltage of approximately 60.9 V and an installed energy of approximately 8.1 kWh per module. This module served as the building block for the subsequent subsystem and pack development.

Final pack design

Following the module evaluation, the selected concept was scaled to pack level. First, an intermediate subsystem was defined, combining nine modules with integrated electrical, thermal, and monitoring functions, resulting in approximately 72.8 kWh of installed energy per subsystem.

The final battery system consists of six identical subsystems (54 modules in total) arranged in a 12P × 189S configuration, providing approximately 728 V nominal voltage and 436.6 kWh installed energy. The modular architecture improves scalability, fault isolation, and subsystem-level monitoring and protection.

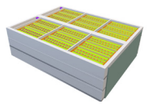
Figure 5 compares the pack concepts developed from the two module architectures and illustrates the impact of cell swelling on system integration. A conventional design requiring 8 mm foam to accommodate the measured 30% swelling achieves a pack-level energy density of 238 Wh/L and 215.9 Wh/kg.

By applying Concept B, the pack-level energy density increases from 238 to 278.9 Wh/L (+17.2%) and from 215.9 to 228.1 Wh/kg (+5.7%) compared with the 8 mm foam concept. At the same time, system weight is reduced by 109 kg (-5.4%) and pack length by 14.7%, with only a minor increase in width (+1.8%).

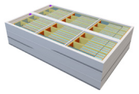
For comparison, the 1.5 mm foam concept represents a theoretical reference case based on the swelling levels typically observed in conventional lithium-ion cells (~8%). Under this assumption, pack-level energy densities of 336.6 Wh/L and 252.4 Wh/kg would be achievable.

This highlights a key finding of the study: while lithium-metal and anode-free cells offer exceptional cell-level energy density, dedicated module and pack architectures are required to manage swelling and preserve as much of the cell-level advantage as possible at the system level.

Concept 1
1.5 mm pad, 8% swelling
8 mm pad, 30% swelling



Concept 2



		Concept	1		2	2 vs. 1
	Property	Unit	1.5 mm	8 mm		With 8 mm foam
General	Cell config.		12P 189S	12P 189S	12P 189S	-
	Mod number		54	54	54	-
	Weight	kg	1729	2,022	**1,913**	-5.4%
Voltage	Minimum	V	567	567	567	-
	Nominal	V	727.7	727.7	727.7	-
	Maximum	V	803.3	803.3	803.3	-
Dimensions	Length	mm	1,773.1	2,552.3	**2,176.0**	-14.7%
	Width	mm	1,370.0	1,370.0	1,394.0	+1.8%
	Height	mm	534.0	516.0	516.0	-
Energy	Installed	kWh	436.6	436.6	436.6	-
	Volumetric	Wh/L	336.6	238	**278.9**	+17.2%
	Gravimetric	Wh/kg	252.4	215.9	**228.1**	+5.7%
Power	Cont charge	kW	218.3	218.3	218.3	-
	Cont discharge	kW	1,309.8	218.3	1,309.8	-

5
Pack concepts developed for the target aviation application based on the two module architectures.

FEV BATT.CODE

Discover FEV's Signature Solution for cell benchmarking.

Conclusion

Lithium-metal and anode-free battery technologies are advancing rapidly. Only a few years ago, cells exceeding 400 Wh/kg were largely limited to laboratory-scale demonstrations. Today, commercial cells with capacities of 50–100 Ah and specific energies above 400 Wh/kg are becoming available, enabling realistic module and pack development.

Progress is not limited to energy density. While the 50 Ah cell investigated in this work reached approximately 100 cycles to 70% capacity retention, FEV's current benchmarking activities already show lithium-metal and anode-free cells achieving improved cycling performance.

New generations of cells are also entering the market. FEV is currently evaluating several next-generation lithium-metal and anode-free cells offering >450 Wh/kg, capacities above 50 Ah, discharge rates above 6C, and operation down to -40 °C.

Despite this progress, cycle life and cell swelling remain key challenges for aviation applications. If swelling can be reduced from today's ~30% range toward 5–10%, significantly less space and weight-intensive swelling-compensation measures would be required at module and pack level. Combined with continued improvements in cycle life, lithium-metal and anode-free technologies could become highly attractive for future electric and hybrid-electric aircraft.

The results presented here represent only a snapshot of a rapidly evolving field. FEV continues its benchmarking, testing, cell-integration, and pack-development activities, and the next generation of these cells is already undergoing evaluation in the company's laboratories. The initial results are highly encouraging.

BY
Dr. Seyedhosein Payandeh
payandeh@fev.com

#3
eDLP: Cross-industry battery testing and validation – *Accelerated development*

The use of lithium-ion batteries has been overshadowed by the rapid transformation in the automotive industry in recent years, but new fields of application have also emerged. Besides replacing other battery chemistries such as lead batteries in UPS (uninterruptible power supply), lithium-based technology has enabled new battery-powered products in rail, marine, and aviation and even new business cases such as the provision of grid services by Battery Energy Storage Systems (BESS).

Regardless of the end-use sector, rigorous testing and validation of performance and safety are an essential part of battery and product development. This is the only way to ensure that the specific requirements of regulations and user profiles can be met.

Here, FEV's benchmark development and testing facility eDLP in Sandersdorf-Brehna, Germany, provides the required infrastructure, processes, and experienced staff to support all challenges associated with battery development – independent of the application. Driven by the extensive automotive testing requirements and high standards for quality and testing continuity, effective processes have been developed since the facility opened in 2020 that allow for the efficient implementation of standardized tests in accordance with established protocols, as well as customized tests to meet specific customer requirements. By leveraging the expertise of FEV's eDLP, costly and time-consuming iterations can be avoided, particularlyin the case of first-time battery developments or startups.

Accelerate time to test

New market entrants and developers of novel battery-powered products often face challenges when defining an effective design verification plan (DVP). Selecting the right validation activities is critical to demonstrating product performance, reliability, safety, and conformity with regulatory requirements while avoiding unnecessary testing effort. In collaboration with the FEV Group, efficient DVPs can be provided, allowing customers to focus on developing the actual product functions while leveraging synergies to minimize test scope and number of devices under test (DUTs).

Experience has shown that most tests fail before they even begin due to communication problems between the test bench and the DUT – a problem further exacerbated by rapid development cycles for DUT software. To avoid costly downtime, the eDLP performs commissioning checks on the DUT before it is brought into the test field as an initial quality gate. Testing communication and contactors, as well as checking insulation and leak tightness outside the test chamber, provides early opportunities for corrective action. Electrical and mechanical modifications to the DUT, performed on-site by experienced technical staff together with the customer, eliminate the need for lengthy shipping of small parts and speed up the start of testing.



Similar regulations across applications

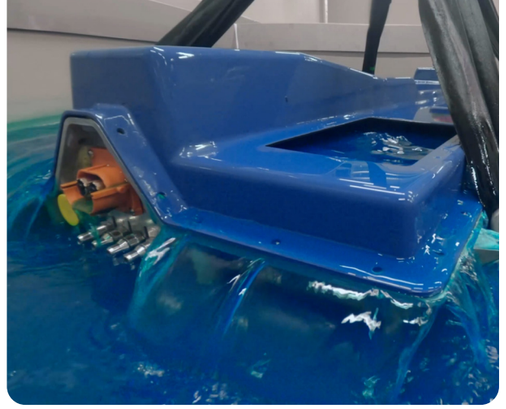
While the application-dependent load profile and battery size might differ significantly, the regulatory requirements for validation tests remain similar across most industries. First, UN 38.3 regulation applies to all battery shipments and defines minimum safety boundaries for every battery development that must be self-disclosed by the manufacturer. Being accredited for the module and pack tests of UN 38.3 according to DIN EN ISO/IEC 17025, FEV's eDLP has a proven record of delivering reliable, high-quality results that support this disclosure.

Second, although different application-specific requirements are reflected in the associated regulations, the covered stress factors remain similar. This is illustrated by Table 1, where the safety scope of UN 38.3 and the automotive standard ECE R100 – already accredited tests at eDLP – are compared with those of other applications. Following the one-stop-shop philosophy, eDLP has built an extensive test infrastructure around automotive-centered demand. However, the comparison reveals that this also enables full test coverage of BESS, marine, and defense products. Due to the lead of automotive battery development, clear elements of the automotive safety requirements defined in ECE R100 have been incorporated into the recent European Battery Regulation for stationary BESS. Similarly, tests from the general IEC 62619 standard are referred to in both VDE 2510-50 (BESS) and EMSA guidelines (maritime).

	Standard	UN 38.3	ECE R100	IEC 62619	VDE AR-E 2510-50	MIL-PRF 32565
	Scope	**Transport**	**Automotive**	**General (industrial)**	**BESS**	**Defense (24 V)**
Mechanical	Vibration	X	X			X
	Shock	X	X			X
	Crush/impact	X	X			X
	Drop			X		X
Environmental	Thermal shock	X	X			X
	Altitude	X				X
	Immersion					X
	Humidity					X
	Sand/dust/salt					X
Abuse	Fire resistance		X			
	Short circuit	X	X		X	
	Thermal abuse					
	Thermal propagation		X	X	X	X
Function	Over-charge	X	X	X	X	X
	Over-discharge	X	X		X	X
	Over-temperature		X	X	X	X
	Over-current		X	X	X	X
	Low-temperature				X	X

Table 1
Comparison of resilience tests addressed in standards beyond automotive application.









Different applications, identical stress factors

When testing batteries, the most basic tests focus on performance under electrical load across varying environmental conditions. Covering demands from small modules to high-performance packs, the test field at eDLP consists of energy systems from 35 kW to 1000 kW and environmental chambers from 800 l to 22 m³ that can be used to simulate operating conditions between -40 °C and 80 °C, depending on the application. If required, FEV can also support the development of application-specific test profiles, as generic bi-directional energy supplies enable the testing of non-battery components such as switch boxes or inverters under controlled ambient conditions.

The comparison of tested stress factors in Table 1 emphasizes the overlap between automotive and other industries beyond mere electrical loads. Thus, infrastructure built with UN 38.3 and ECE R100 in mind, such as in the case of the eDLP, is well suited to test beyond automotive applications. This is especially important from a development cost perspective, since non-electrical tests are characterized by highly specialized test stands often tailored to just one specific test.

Non-automotive but mobile products, such as those used in rail, marine, or defense applications, are commonly stressed by application-specific vibration profiles which emulate the mechanical lifetime loads. The 350 kN-shaker at eDLP is not only rare because of its size, but, when equipped with a climatic chamber and energy supply, it also enables complex combination of mechanical, thermal, and electrical loads.

Environmental stress factors are tested with respect to their impact on performance and lifetime, including exposure to extreme temperatures as well as the battery housing's resistance to water ingress, corrosion, and fast temperature changes. While products in controlled environments (e.g., indoor BESS) are, in general, less rigorously tested, defense standards impose extensive operational ranges. With its comprehensive array of environmental tests, eDLP can emulate most expected extreme operational conditions for battery-powered systems, including water immersion, exposure to salt or sand, and low-pressure conditions encountered in aerospace.

Small deviations with large consequences

The stresses are mainly reflected by internal changes within the battery pack or even the cells themselves and therefore hidden from the outside. Low-pressure tests as required, for example, by UN 38.3, in defense or aerospace conditions might cause slight cracks in the sealed housing that do not directly impact safety or function, but that can accelerate degradation and ultimately pose a safety risk. Hence, identifying and assessing these changes is mandatory to derive the necessary engineering measures in the development process. Experts at eDLP dismantle DUTs after tests and inspect components – supported by 3D-scanning – down to cell level to document even minor impacts of the test. Dismantling further allows for in-depth analysis of individual components by CT-scanning to identify internal degradation. This tool reveals structural changes in the cell layers and can therefore be used for a more granular assessment of cells unaffected by thermal propagation, which is particularly relevant for BESS scenarios.

Streamline testing in every development stage

Product validation requires battery testing to begin early in the development process – at a stage where the battery management system (BMS) or even the housing may still be under development. Building on years of experience in battery development, FEV eDLP supports customers with a customizable BMS interfaced with the test automation system. This allows not only early component tests, but also provides an environment for evaluating different control strategies. Here new market entrants such as start-ups in the defense and aerospace sectors can benefit from test results while still developing their core functions. Test rigs or prototypes, on the other hand, require specialized knowledge to enable testing of the actual part in question and prevent interferences from the test setup. Leveraging years of experience at FEV can make the difference between reliable results and costly test stand development iterations.

The deep integration of test execution into the automation system guarantees deterministic tests without manual intervention, including automatic data conversion, post-processing, and provision of test data. Through this, time between test execution and results is minimized and the market entry accelerated. In addition to extensive automation, 24/7 operation at eDLP by experienced staff enables fast updates of test plans or intervention in case of challenges.

»Different industries. Similar stress factors. One infrastructure to accelerate battery validation.«

Conclusion

Due to the broad coverage of common stress factors encapsulated by eDLP, the requirements of non-automotive industries can be fulfilled in one location. This allows for an optimized handling process from test development and prototype design, to commissioning and inbound check after arrival, automated test execution, and in-depth assessment on-site after testing. Thus, there is no need to transport batteries of unknown condition, handovers are minimized, and results are available faster. In aggregate, these factors can be the difference between an on-time successful product launch and the type of expense that can destroy an otherwise promising product or company.

BY
Andreas Geistert
geistert_a@fev.com
Jacob Klink
klink_j@fev.com

One partner
One facility
One team



15,000 m²

eDLP: FEV's testing & development center for HV batteries

ISO/IEC 17025 accreditation

150+
different battery designs tested

1,500+
major testing programs executed

60+
Integrated test benches

Concept to SOP

20+
Years of global battery validation expertise

350+ kN Shaker

edlp.fev.com

Find out more about the eDLP



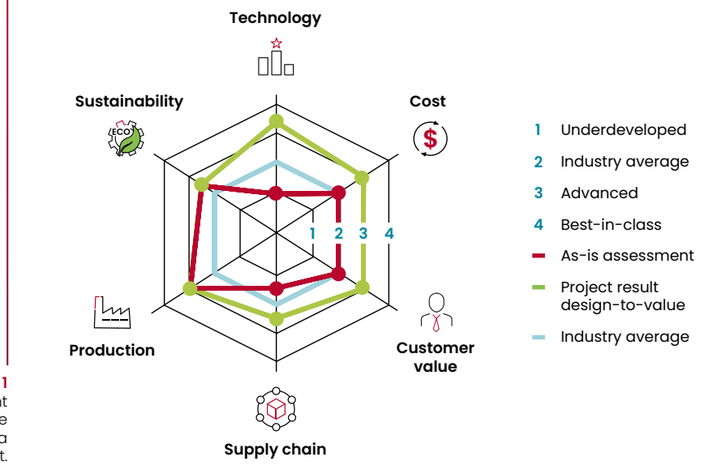
#4
Design-to-value for competitive *battery development*

Electrified product development has reached a level of complexity where traditional optimization approaches no longer suffice. Battery systems require simultaneous consideration of technology, cost, customer value, sustainability, production, and supply chain. Yet in many development programs, these dimensions are still treated in isolation.

A recent battery project conducted by FEV illustrates how a design-to-value (DtV) approach can address this challenge. Drawing on FEV's expertise in battery development, benchmarking, cost engineering, and market analysis, the project followed a structured process from initial assessment to measurable business impact. The project demonstrates how a battery system can be evaluated from multiple perspectives and transformed into alternative product concepts that enhance both customer value and profitability.

Establishing transparency across all dimensions

The starting point was a structured assessment conducted by FEV to evaluate the battery system across the six aforementioned dimensions: technology, cost, customer value, sustainability, production, and supply chain. The assessment revealed the largest improvement potential in technology, supply chain robustness, cost competitiveness, and customer value, while production maturity and sustainability were already comparatively strong. Overall, the battery system remained technically competitive but no longer offered an optimal balance between cost, customer value, and market requirements.



1 360-degree assessment of the design-to-value dimensions shown as a spider chart.

1 Initial assessment & scoping

Understanding root causes at system level

Building on the initial assessment, FEV performed a deeper analysis of the battery architecture to understand the drivers behind the identified competitiveness gaps.

The analysis showed that several challenges originated from system-level design decisions rather than individual components. The combination of cylindrical 21700 cells and the chosen module layout, for example, resulted in a suboptimal volumetric cell-to-pack ratio, particularly in the vertical dimension of the battery pack. In addition, conservative thermal management and propagation concepts increased cost and system weight.

These findings highlighted that the improvement potential was primarily rooted in the overall battery architecture and would therefore require a holistic optimization approach.

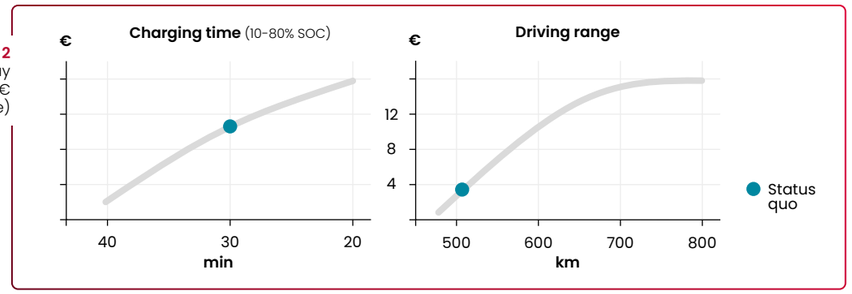
2 Status quo analysis

Understanding cost drivers and customer value

Following the initial assessment, FEV deepened the analysis from both a cost and customer perspective. A detailed should-cost analysis was conducted to identify the main cost drivers within the battery system and benchmark them against competitive solutions. In addition, FEV performed a willingness-to-pay assessment based on a choice-based conjoint survey of end customers to quantify the value attributed to different battery characteristics and their impact on market attractiveness.

The should-cost analysis revealed the primary architectural and component-level drivers behind the battery system's cost position. In parallel, the willingness-to-pay assessment quantified the economic value attributed to key battery characteristics such as driving range, charging time, and battery lifetime, while also highlighting how customer priorities differ across market segments, usage profiles, and regions.

For the evaluated customer segment, the analysis revealed significant differences in the value attributed to individual battery characteristics. In particular, the results highlighted a comparatively high willingness to pay for additional driving range and reduced charging time.

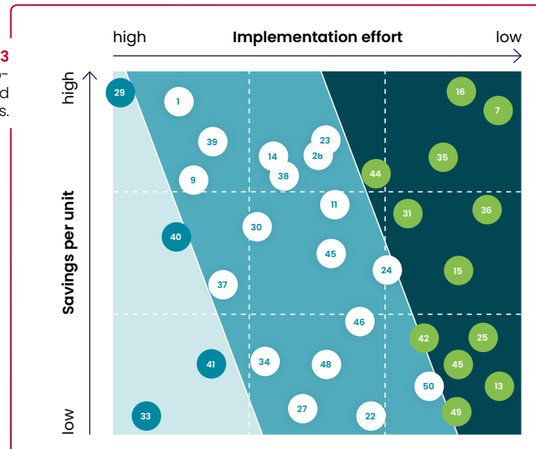


2 Willingness-to-pay analysis (additional € per feature)

3 Ideation & prioritization

Generating and prioritizing improvement measures

Based on the technical, commercial, and customer insights, FEV facilitated interdisciplinary workshops involving battery experts, cost engineers, and customer representatives to identify improvement opportunities across the system. More than 80 improvement ideas were generated, ranging from targeted component optimizations to fundamental architectural changes.



3 Excerpt of the design-to-value idea portfolio and prioritization process.

»Profitability is determined not only by cost, but by the balance between cost, customer value, and achievable price.«

The workshops combined findings from the technical assessment, benchmarking activities, customer value analysis, and expert knowledge from different engineering disciplines. Figure 3 illustrates an excerpt of the resulting idea portfolio and the subsequent prioritization process.

To identify the most promising opportunities, FEV evaluated each measure with respect to cost impact, customer value, implementation effort, and technical risk. The outcome was a prioritized portfolio of short-, mid-, and long-term measures, providing a transparent basis for the development of future battery concepts.

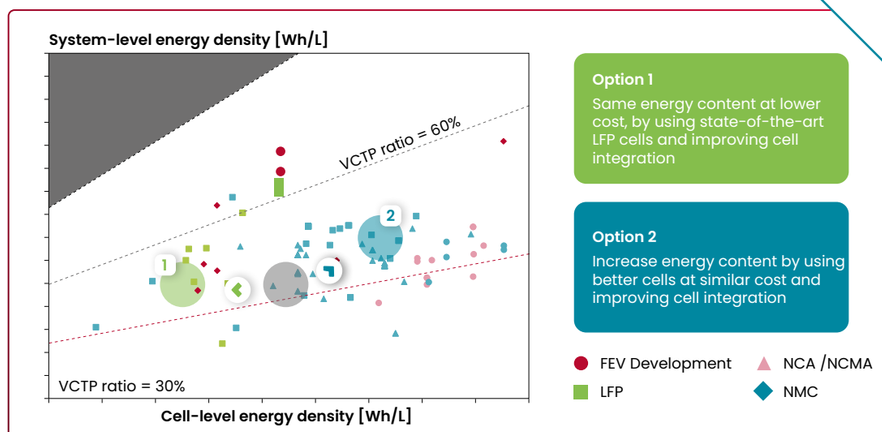
From improvement measures to design concepts

FEV consolidated the identified measures into two battery concepts aligned with different market requirements.

The first concept focused on cost optimization. By transitioning to state-of-the-art LFP cells and improving system integration, the overall energy content was maintained while significantly reducing system costs. This approach targets cost-sensitive market segments where affordability is a key purchasing criterion.

The second concept followed a value-oriented strategy. By upgrading to a more advanced NMC cell generation and combining it with optimized packaging and improved space utilization, the battery achieved a higher usable energy content and extended driving range. The newer cell generation also enabled improved charging performance compared with that of the original battery design.

This connection between customer preferences and technical design decisions was a central outcome of the DtV process. The willingness-to-pay assessment highlighted significant value potential in customer-relevant attributes, particularly those related to driving range and vehicle usability. Consequently, the objective was not simply to maximize technical performance, but to selectively invest in features that create the greatest customer value and support a stronger market position.



4 Alternative battery concepts resulting from the design-to-value process.

4

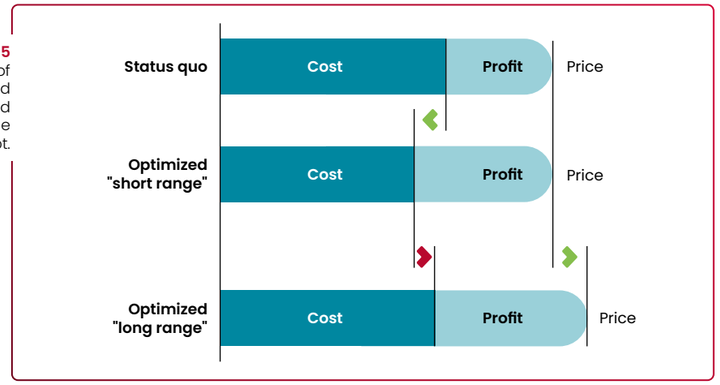
Business case analysis

Quantifying business impact

To support decision-making, FEV consolidated the technical findings, prioritized improvement measures, and customer value insights into an integrated business case model. The model considered system cost, investment requirements, achievable market price, and resulting profitability.

The evaluation confirmed that both battery concepts outperformed the status quo. While the short-range concept benefited primarily from a lower cost base, the long-range concept leveraged a higher achievable market price resulting from the additional customer value it offered.

The comparison highlights a key principle of DtV: profitability is determined not only by cost, but by the balance between cost, customer value, and achievable price. A technically more expensive product can therefore create a stronger business case if the added value is recognized and rewarded by the market.



5
Business case comparison of status quo, cost-optimized short-range concept, and value-optimized long-range concept.

4

Implementation support

From analysis to implementation

The final step focused on translating the selected measures and design concepts into actionable implementation plans. FEV supported this transition by defining clear roadmaps, responsibilities, and tracking mechanisms to ensure that the identified value potential could be realized in the development process.

This implementation phase is critical because the true impact of DtV is not created by analysis alone, but by bringing the selected measures into engineering practice. For each measure, the required activities, technical dependencies, potential risks, and decision points were defined. This created transparency on what could be implemented in the next design update, and which measures required a longer development horizon.

Close collaboration between consulting, engineering, purchasing, and customer teams was essential. It ensured that design decisions remained aligned with both technical feasibility and business objectives. At the same time, early engineering validation helped reduce the risk of late-stage adjustments and supported a more robust path toward implementation.

In this way, DtV became more than a decision-making framework. It provided a structured bridge from analysis to execution, helping transform identified improvement potential into measurable product and business impact.

Conclusion

The project demonstrates how FEV's Design-to-Value approach can transform product development by connecting technical, commercial, and customer perspectives within a single decision framework.

Starting from a structured assessment of technology, cost, customer value, sustainability, production, and supply chain, FEV systematically identified the root causes limiting competitiveness. Combining technical analysis, customer research, and business case evaluation enabled the project team to move beyond isolated optimizations and develop product concepts aligned with clear market objectives.

One of the most important insights from the project is that there is rarely a single "optimal" solution. In this case, both the cost-optimized and the value-optimized battery concepts improved profitability, but through fundamentally different mechanisms. One created value by reducing costs, while the other leveraged increased customer value and willingness to pay.

As markets become more fragmented and customer expectations more diverse, the ability to evaluate such trade-offs systematically will become increasingly important. The challenge is no longer to optimize individual product attributes in isolation, but to identify the combination of technical features, cost structures, and customer benefits that creates the strongest overall business case.

By translating complexity into transparent decisions, DtV provides a practical framework for developing more competitive and more profitable products.



BY
Benjamin Knobloch
knobloch@fev.com
Felix Wiesemann
wiesemann@fev.com
Kevin Poch
poch@fev.com
Michael Quast
quast_m@fev.com

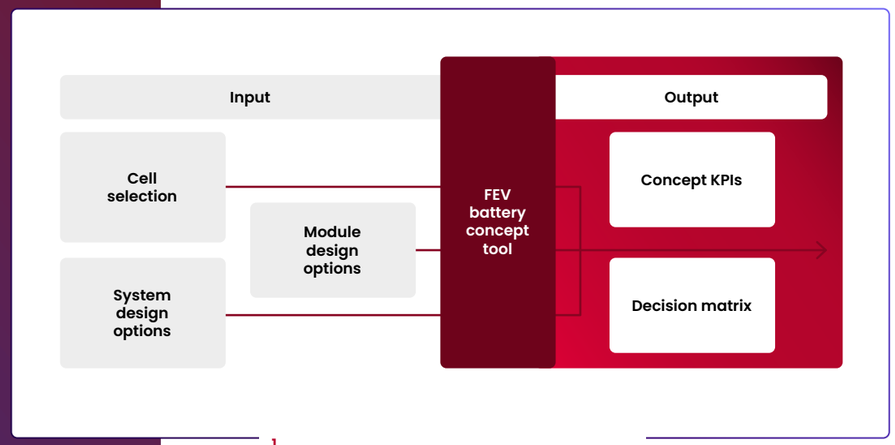
#5
Concept development for ***scalable battery energy storage systems*** with BATT.code



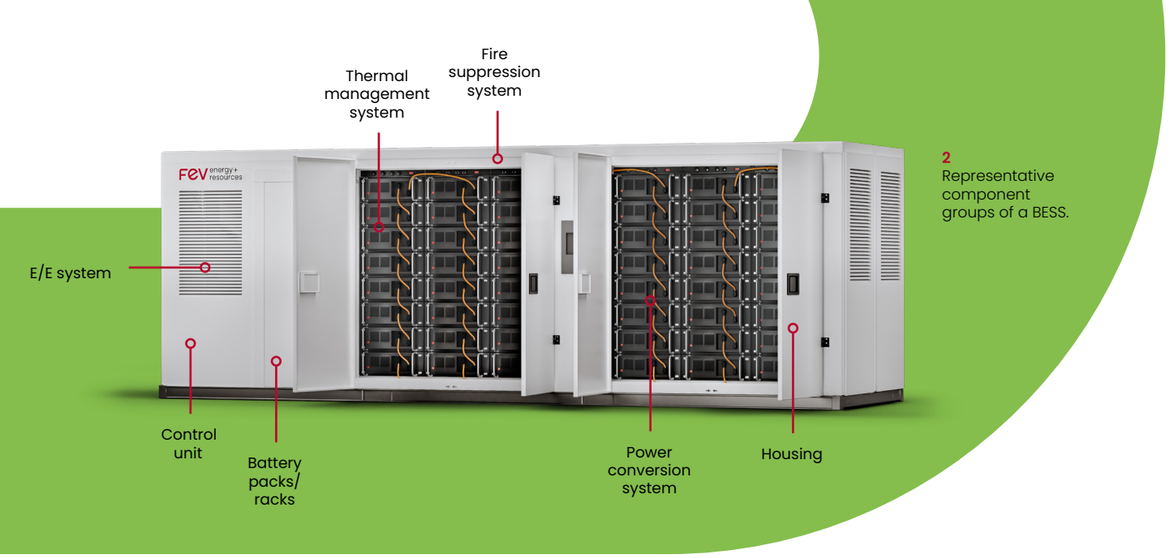
FEV
BATT.CODE

The expansion of renewable energy is reshaping power systems worldwide. As wind and solar generation continue to grow, the ability to store energy efficiently, safely, and economically becomes a decisive factor for grid stability, energy security, and the successful integration of fluctuating generation profiles. Battery energy storage systems (BESS) are therefore moving from niche applications into the center of future energy infrastructure. They support frequency regulation, peak shaving, renewable energy integration, backup power and, increasingly, also large-scale commercial and industrial use cases.

BESS concepts must balance energy content, power capability, thermal management, fire protection, installation space, serviceability, cost, and compliance with project-specific boundary conditions. Decisions made in the early concept phase strongly influence achievable performance, total cost of ownership and later engineering effort. Against this background, FEV is extending its battery concept development environment BATT.code from mobile battery pack applications to stationary energy storage systems. The objective is to support early concept decisions with a structured engineering workflow that enables virtual cells, modules, packs and BESS layouts to be generated, evaluated and compared on a consistent technical basis.



1
FEV battery concept development methodology



2 Representative component groups of a BESS.

From automotive battery concepts to stationary storage

BATT.code was originally developed for battery concept studies in the automotive sector. In this environment, battery packs are typically designed around vehicle-specific package spaces and application requirements. The external dimensions of the pack result from the interaction of cells, modules, structural elements, cooling systems, and electrical components. This bottom-up logic is well suited to comparing battery concepts at an early stage because it links cell selection, module design and pack integration to measurable system KPIs. The underlying workflow follows a systematic sequence from virtual cell creation to module derivation, pack aggregation, one-page concept reporting, and matrix-based comparison of alternatives (Figure 1).

Stationary storage systems follow a different logic. Instead of optimizing a battery pack for vehicle architecture, BESS concepts are often developed within predefined container dimensions and infrastructure constraints. Typical projects start with standardized formats such as 20-, 30- or 40-foot containers, available installation areas, required grid connection power or target energy content. For this reason, the BESS extension of BATT.code introduces a top-down approach for the newly developed BESS layer. The available container envelope is defined first, and the system configuration is then developed inside this boundary.

A top-down concept workflow for containerized storage

The new BESS functionality enables concept engineers to define fixed container formats and populate them with battery racks and typical stationary storage components. This includes not only the electrochemical storage units, but also the system elements required to operate a complete containerized energy storage solution (Figure 2). These comprise HVAC units, inverter interfaces, fire protection hardware, rack structures, electrical distribution and monitoring components. By representing these elements from the start, the tool supports a system-level view instead of a simplified battery-only layout.

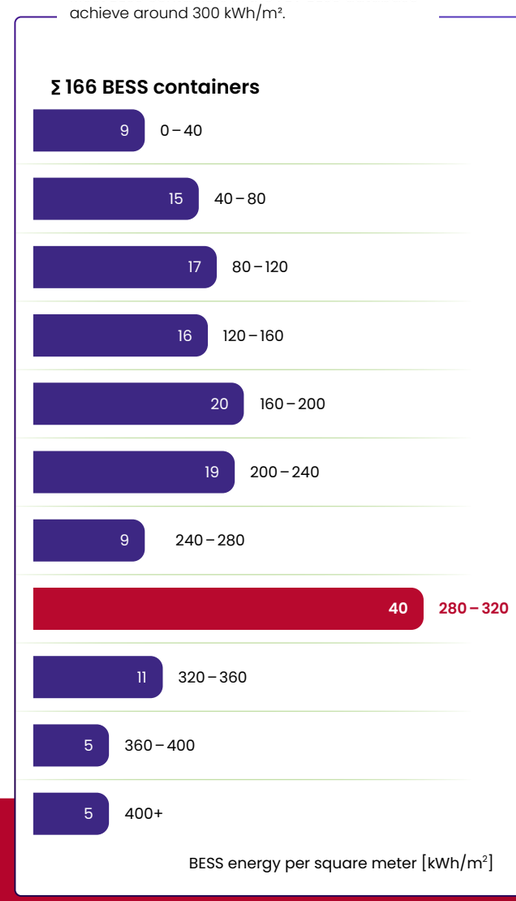
This approach is particularly useful in early-phase development, when different design options must be compared quickly while still relying on consistent engineering assumptions. Engineers can evaluate how changes in cell format, rack arrangement, container size, service concept or auxiliary component allocation affect key performance indicators. For example, a concept based on a 20-foot container may prioritize compact installation and modular deployment, while a 40-foot concept can offer higher total energy content. Through iterative layout and evaluation steps, the workflow supports concept development, building on experience gained in previous and ongoing industry projects. Variants can be generated, assessed, adapted and compared in short cycles instead of being built manually in isolated spreadsheets.

Engineering KPIs that matter in the concept phase

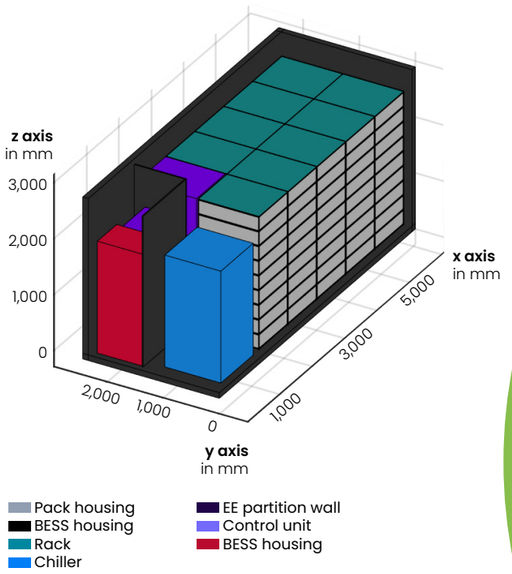
For BESS applications, early concept work must go beyond calculating the nominal energy content of cells. A practical storage concept needs to address usable energy, packaging performance, system volume, mass, thermal integration, safety-relevant space reservations and the arrangement of functional components. BATT.code is being expanded to make these relationships visible in a structured way. The objective is to evaluate how much energy can be integrated into a given container format and which design assumptions have the strongest influence on the result. Typical outputs include dimensions, gravimetric and volumetric energy density, electrical performance indicators and the degree of requirement fulfillment, enabling concept teams to compare what was requested with what the layout can realistically deliver.

As illustrated in Figure 3, benchmark data from the FEV BESS Database BATT.KPI shows that a large share of containerized systems achieve an area-related energy density of around 300 kWh/m². This provides a useful reference range for assessing whether a new concept is aligned with current market solutions. By linking layout generation with KPI calculation and benchmark comparison, BATT.code enables project teams to discuss these trade-offs on a common technical basis and prepare decisions for subsequent development phases. For BESS applications, this data-driven approach is being extended with information on more than 250 stationary storage products, container configurations, energy content and system architectures currently available on the market. The goal is to connect internal concept modeling with external benchmark references so that new concepts can be evaluated against realistic industry examples.

Such a database supports questions that are highly relevant in early customer discussions: Which energy contents are typical for containerized BESS solutions? How do different container sizes compare? Which packaging concepts are currently available on the market? Where do concept results appear ambitious, conservative or aligned with benchmark ranges? By combining calculation models with benchmark evidence, FEV's BATT.code can support both engineering feasibility assessments and communication with non-specialist stakeholders.



3 Most BESS containers in the FEV BESS database achieve around 300 kWh/m².



4
Exemplary 3.4-MWh concept for a 20 ft containerized BESS.



review a complete concept logic: predefined container dimensions, selected storage architecture, component allocation, resulting energy content and relevant system KPIs. This enables more objective trade-off discussions and reduces the risk that early decisions are based on incomplete or inconsistent assumptions. An example is shown in the 3D visualization in figure 4, illustrating a 20-foot 3.4-MWh stationary storage container with an integrated chiller, power electronics, and fire protection equipment. This example also demonstrates how subunits or packs can be integrated into a rack structure to enable repairability and serviceability of subunits without decommissioning the whole container.

BY
Tobias Klerks
klerks@fev.com
Janis Vienenkötter
vienenkoetter@fev.com
Till Banning
ext_banning@fev.com

Supporting faster and more transparent decisions

The value of a digital concept tool lies not only in calculation speed, but also in the transparency of assumptions. Stationary storage projects involve several engineering disciplines, including electrical engineering, thermal management, safety, mechanical packaging, system integration and commercial project planning. BATT.code can serve as a common engineering backbone for these discussions by making design assumptions explicit, allowing variants to be compared consistently and helping teams identify the technical drivers behind differences in performance or package efficiency. This supports the transition from individual design ideas to well-founded concept decisions.

This transparency is especially important when concepts need to be aligned across internal teams, customers, and partners. Instead of discussing isolated figures, teams can

»By combining calculation models with benchmark evidence, FEV's BATT.code can support both engineering feasibility assessments and communication with non-specialist stakeholders.«

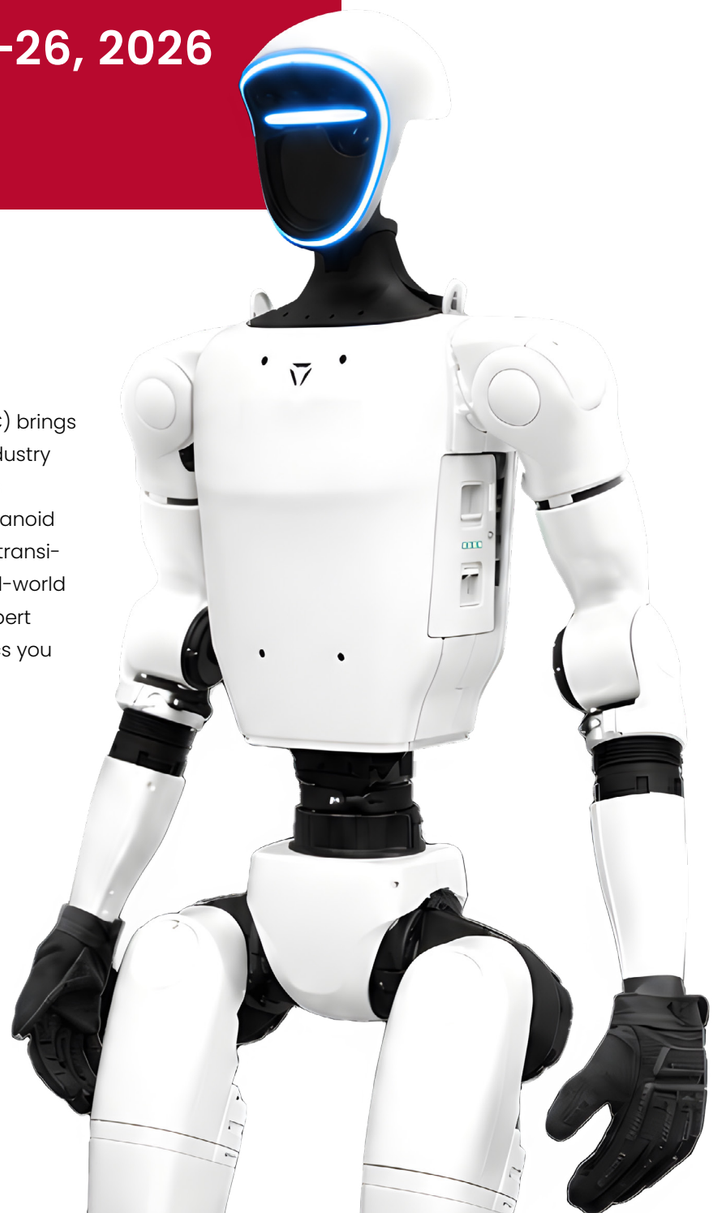
Conclusion

The demand for stationary energy storage will continue to grow as energy systems become more decentralized, renewable and flexible. At the same time, BESS will need to become more compact, cost-efficient, safe and scalable. For OEMs, system developers and project decision-makers, this increases the need for transparent concept evaluation before detailed engineering work begins. In this context, robust early-phase evaluation of container format, rack architecture, component allocation and usable energy content becomes essential to ensure that BESS concepts remain technically feasible, economically viable and scalable across different project conditions. By combining container-based concept modeling with component-level system thinking and market-oriented KPI evaluation, BATT.code provides a structured basis for turning storage requirements into technically sound concepts. The tool is not positioned as a replacement for detailed CAD engineering, but as an enabler for more robust early-phase decisions. It helps development teams translate market requirements and project constraints into comparable system concepts, thereby strengthening the link between benchmark data, engineering feasibility, and practical implementation.

ARC 2026

ADVANCED ROBOTICS CONFERENCE

November 25-26, 2026
FEV Aachen



The next evolution starts now.

The Advanced Robotics Conference (ARC) brings together leading minds from robotics, industry and research to explore the technologies shaping the next era of automation: humanoid and mobile robotics, Physical AI, and the transition from technological innovation to real-world industrial application. Expect inspiring expert insights, high-level exchange and robotics you can experience first-hand – bringing the future of robotics closer to reality.

Meet Our Speakers

Jochen Rudat
Chief Growth Officer
Humanoid

Arne Nordmann
VP Technology
NEURA Robotics

Steven Palma
Robotics Lead
Hugging Face

Jérôme Monceaux
CEO & Co-Founder
Enchanted Tools

Christian Piechnick
CEO & Co-Founder
Wandelbots

Wilhelm Lindgren
VP Humanoids EU
Schaeffler

Simon Fischinger
CEO
Synapticon

Vincent Yang
CEO & Founder
Prologium

Alfred Larsson
Director Strategic Accounts
Sereact

Enno Dülberg
CEO & Founder
AUXSYS

Oliver Petrovic
CEO & Co-Founder
Athenyx Robotics

Daniel Kottlarz
CEO
MYBOTSHOP / Quadruped Robotics

Jack Pearson
CEO
RoboStrategy

Werner Kraus
Leiter Forschungsbereich
Automatisierung & Robotik
Fraunhofer IPA

Dirk Geiger
Senior Director Application
Marketing for Humanoid Robotics
Infineon

BE PART AND REGISTER NOW

fev.com/arc-2026

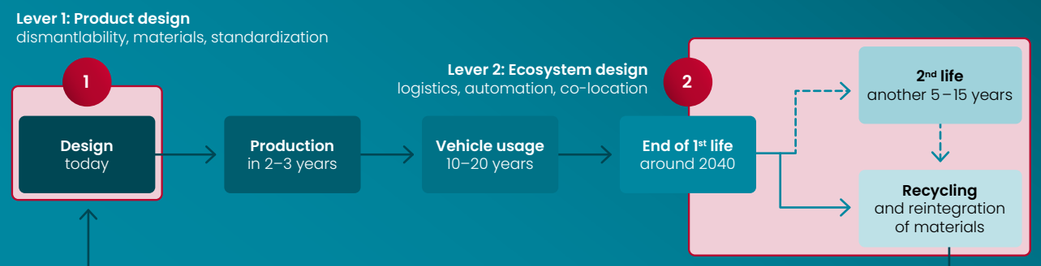
SPEACHES
PANEL DISCUSSIONS
ACTION AREA
EXHIBITIONS

#6 *Beyond recycling:* Engineering the second life of batteries

Battery circularity is often discussed in terms of recycling, but the real economic potential extends far beyond the recovery of materials. FEV's CycleBat model suite shows that designing a battery for circularity can swing its end-of-life economics by more than 1,650 EUR per pack.

One finding is particularly important: under today's business models, a majority of end-of-life batteries are projected to go straight to recycling. Not because they are technically exhausted, but because the business case for second-life applications often does not close.

Changing this outcome requires looking beyond the battery itself. The economic viability of battery circularity is determined by two levers: the design of the battery at the start of life, and the design of the ecosystem that receives the battery after its first life. The first lever determines much of the potential for circularity. The second is where the industry's biggest untapped value may lie.

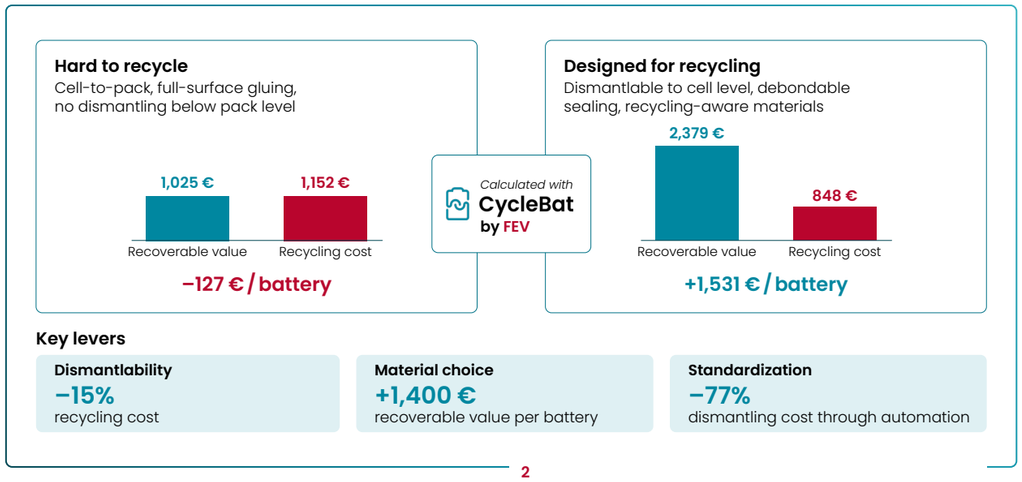


1
The two levers of circular battery economics: product design at the start of life, ecosystem design at the end of first life.

Lever one, revisited: design sets the ceiling

A short recap, because the two levers are connected. A battery developed today will be produced in two to three years and used in a vehicle for ten to twenty years before being removed and dismantled. Current design trends make that last step difficult, as cell-to-pack and cell-to-chassis architectures improve energy density, but their structural adhesives and welded joints are expensive to take apart — a lesson FEV's benchmarking experts have learned time and again, for example during the teardown of the BYD Seal's highly integrated battery pack. A pack that cannot be dismantled must be shredded whole, which raises processing cost and degrades the recovered material.





2
Design determines value: recycling economics of an 80-kWh pack in the projected EU recycling market of 2040 – a swing of more than 1,650 EUR per pack (CycleBat Designer).

The CycleBat Designer puts numbers on this. For an 80-kWh pack in the projected European recycling industry of 2040, a hard-to-recycle LFP cell-to-pack design ends its life 127 EUR in the red, with recycling costs of around 1,152 EUR against 1,025 EUR of recoverable value. An NMC pack of the same capacity designed for recycling, dismantlable to cell level with a debondable sealing concept, recovers 2,379 EUR against 848 EUR of cost, a positive value of more than 1,500 EUR. Three principles carry the swing: dismantlability, conscious material choice, and standardization. Under the EU Battery Regulation's Extended Producer Responsibility, the FEV CycleBat difference lands on today's balance sheet, not on a future operator's.

What design cannot fix on its own is the second-life problem. And that problem is worth fixing, because recycling is not the only exit from the vehicle.

Second life: a good idea with a broken business case

A traction battery typically retires from automotive duty at 70–80% of its original capacity. Too little for a car, plenty for stationary storage, where weight and volume barely matter. Grid buffering, commercial peak shaving, solar self-consumption, charging infrastructure: the applications are real, and so is the demand for cheap storage capacity.

The problem is the cost of getting there. Before a used pack delivers its first kilowatt hour of stationary service, it has been collected, transported as dangerous goods, tested, graded, in many cases dismantled to module level, reassembled, and certified. FEV's CycleBat Value Chain tool shows it clearly: this cost stack pushes second-life systems uncomfortably close to the falling prices of new battery storage, which can be below 100 EUR per kWh for large-scale systems. For nickel-rich chemistries, the contained metals are even valuable enough that recyclers can outbid repurposers for the same used pack, while for LFP the metals are worth so little that recycling alone is unattractive.

The market's answer so far has been to work around true end-of-life rather than with it. Voltfang, for example, builds its storage systems from used modules with more than 80% residual capacity. Many programs rely on what could be called second-chance batteries: near-new packs from prototype vehicles, warranty returns, and pre-series or overproduction. A sensible entry point, but not yet a circular economy. The batteries that will arrive in volume are genuinely aged, and a model that only works with the young ones will not scale. This is precisely why the projections show most packs skipping second life today.

»Under the EU Battery Regulation's Extended Producer Responsibility, the FEV CycleBat difference lands on today's balance sheet, not on a future operator's.«

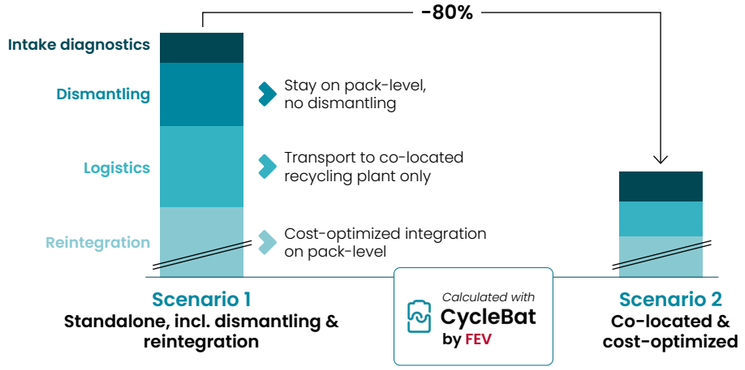
The second lever: co-designing second life and recycling

The standalone second-life calculation contains a hidden double payment. Every one of these batteries has to be transported and dismantled eventually anyway, because recycling is its final destination regardless of what happens in between. A standalone repurposer pays for collection, transport, and dismantling to get the battery into second life, and the recycler pays for transport all over again when the battery finally gives out.

Co-locating second-life operations with a battery recycling facility removes that duplication. The battery travels once, to a site where diagnostics at the intake gate decide its route. Packs with usable capacity are integrated into stationary storage on site and operated until true end of life. Recertification and remarketing become unnecessary as second life and recycling are handled by the same entity. Logistics and dismantling are carried once, by the recycling flow that had to bear them anyway, and the incremental cost of second life shrinks to grading and integration. Second life stops being a separate business fighting for its own viability and becomes a revenue stage in front of the shredder: years of additional service extracted from an asset that was already paid for and already on site.



[Battery recycling]



3
Cost-optimized battery second life: co-locating and optimizing the reintegration approach reduces second-life cost by 80%, enabling economically viable operation even for batteries at true end-of-life.

The effect goes beyond cheaper repurposing for the packs that would have qualified anyway. Because the incremental cost drops, the state-of-health threshold at which reuse beats immediate recycling moves down. Batteries a standalone repurposer would reject become economically viable to operate for a few more years, since keeping them costs little more than the grading effort. That is what turns "a majority goes straight to recycling" from a projection into a choice.

Successful recycling and second-life players are converging on this logic. Redwood Materials repurposes batteries with more than 50% remaining capacity at pack level with minimal effort into modular storage systems and feeds them into its own recycling operation at true end of life. Its 12 MW / 63 MWh microgrid with Crusoe, powering an AI data center in Nevada, USA, ranks among the largest second-life deployments in the world. BeePlanet in Spain, previously specialized in battery storage and second life, is adding a 10,000-ton-per-year recycling plant to close the loop in-house. B2U attacks the same cost stack from another angle, deploying intact vehicle battery packs in large-scale storage applications without reconfiguration. Different starting points, same insight: the money is made where reuse and recycling share infrastructure.

Making this work operationally is a genuine engineering task. Intake diagnostics must be fast and automated, because manual testing consumes the margin. Storage integration has to handle mixed chemistries and states of health. Routing needs to be chemistry-aware: LFP packs, with their long cycle life and low material value, are natural reuse candidates, while a high-nickel pack may earn more in the furnace when metal prices are high. To maximize revenue potential, second-life battery assets must be strategically positioned in the market, considering their technical characteristics, target applications, and market demand. Layout and logistics must be optimized to minimize add-on cost while maximizing asset utilization.

And here the two levers close into one loop: a pack designed for dismantling is not only cheaper to repair during the first life, but also cheaper to repurpose, and cheaper to recycle. Design decisions made in 2026 determine how well the integrated sites of 2040 will run.

Engineering the loop closed

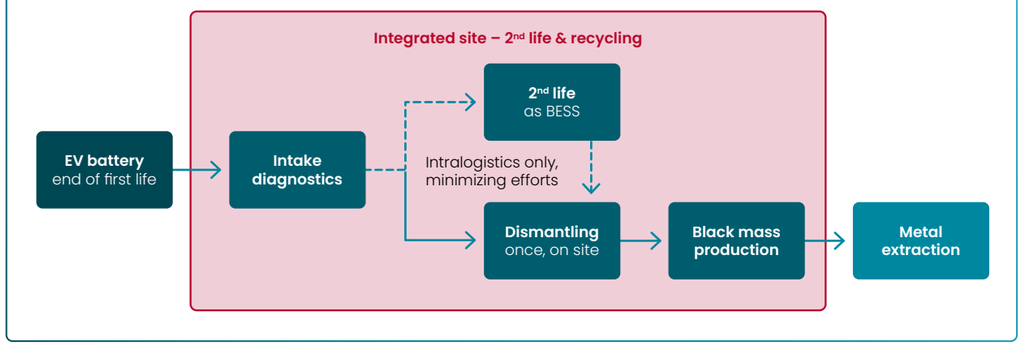
FEV supports clients on both levers, and the combination of deep expertise and extensive experience creates real value here. The CycleBat suite delivers the quantitative backbone: forecasting end-of-life volumes, calculating cost and carbon footprint along every process step, and weighing recycling economics against second-life potential for a specific battery at a specific site and point in time. What makes this rare is what sits next to it. FEV's battery engineering and benchmarking teams design battery systems and components, tear down competitor packs, and know from the workshop floor what dismantling actually costs. Model results translate directly into design measures and site concepts. Few advisors can both calculate the routing decision and engineer the pack and the facility it runs through.

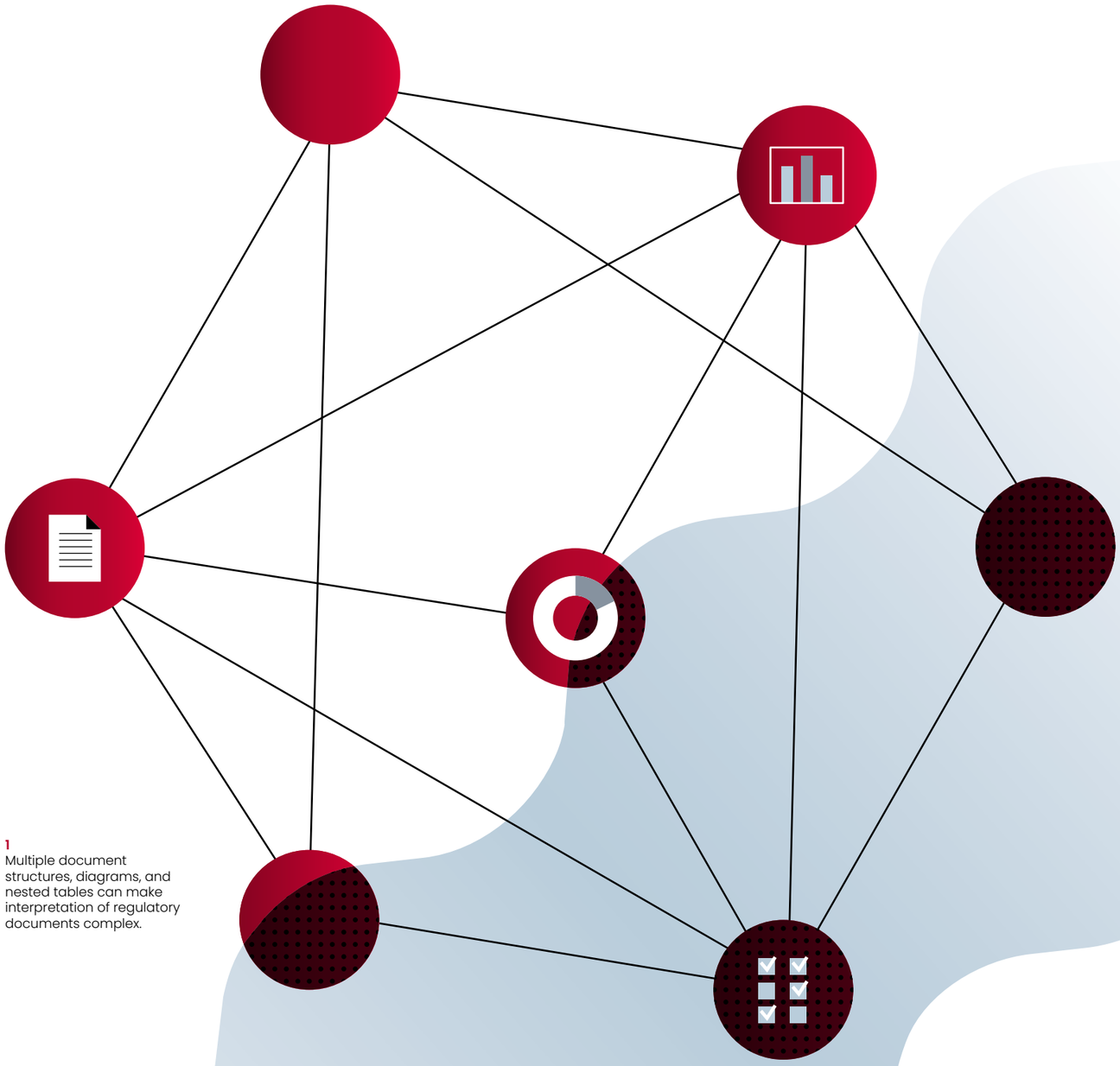
The approach is proven across the value chain. For a European commercial vehicle OEM, FEV modeled remanufacturing, repurposing, and recycling pathways over eight value chain steps and calculated second-life business cases for both NMC and LFP packs, down to an implementation roadmap. For an Asian recycler entering the European market, CycleBat identified the optimal plant location and capacity ramp-up. And for a global vehicle manufacturer, FEV's experts mapped the second-life landscape in Europe, from players and regulation to the cost per kilowatt hour of each end-of-life route.

The message of the CycleBat article in SPECTRUM 83 was that circularity has to be designed into the product. The message of this article is that it also has to be designed into the ecosystem. Neither lever works fully without the other, and both are set long before the first battery reaches the gate. The closed-loop future will not arrive because regulation demands it. It will arrive when the economics work, and the economics can be engineered.

BY
Markus Volkening
volkening_ma@fev.com
Kilian Sagner
sagner@fev.com

4
One site, one journey: intake diagnostics route each pack to second-life storage or directly to recycling; storage assets roll into the recycling line at true end of life.





1
Multiple document structures, diagrams, and nested tables can make interpretation of regulatory documents complex.

#7 *Requirements at a click:* How agentic AI turns norms and standards into traceable engineering requirements

Engineering teams must translate a growing body of regulations, norms, and standards into precise requirements. Yet the relevant information is distributed across paragraphs, annexes, tables, figures, and cross-references. FEV's Regulation Analysis Assistant combines structured document processing with specialized AI agents to create reviewable requirements and preserve their traceability. An expert evaluation on Euro 7 shows why this controlled workflow is more reliable than simply asking one large language model (LLM) to interpret the complete document in a single step.

Requirements are hidden in documents

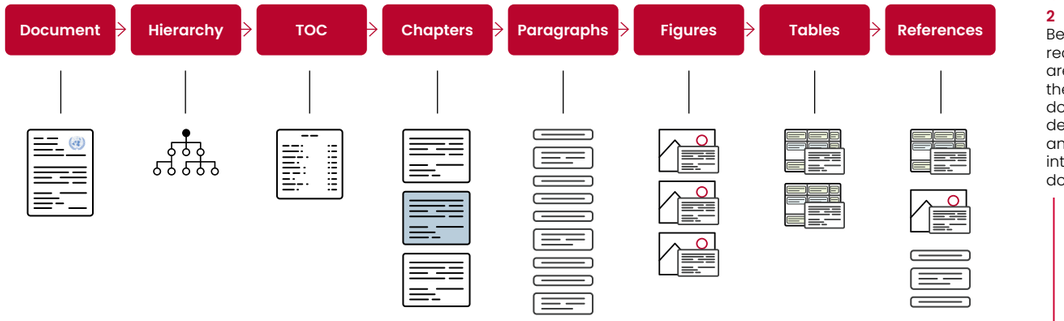
Regulations, norms, and standards are not written for direct import into a requirements management system. They describe responsibilities, exceptions, limits, and test conditions for different stakeholders. An obligation may refer to an earlier definition, a limit value in an annex, and a table that distinguishes vehicle categories. A diagram can add information not repeated in the text. Reading only the apparent "requirement sentence" can therefore change its meaning.

Experts identify these relationships largely by navigating documents page by page and transferring relevant content into requirements tools. Their domain knowledge is indispensable, but the surrounding search and documentation work is time-consuming and repetitive, especially when repeated for another vehicle variant, market, or document version. A missed condition creates an incomplete requirement; a lost source link complicates clarification, audits, and change analysis. LLMs can interpret natural language and formulate engineering-oriented statements. However, a plausible list is not yet a dependable engineering result. Completeness, context, and provenance must be controlled as deliberately as the wording itself.

Why one prompt is not enough

The simplest approach is to give an LLM the complete document and ask for all relevant requirements. Modern models can produce useful results this way, especially for concise documents. But there is little control over whether every section has been considered. Long inputs dilute attention, while tables, figures, hierarchies, and cross-references may be interpreted only partially. The output can sound convincing despite omissions or material outside the intended scope. Complex standards may contain several tables of contents, reuse appendix numbers, embed tables within tables, or mix scanned pages with selectable text. These structures determine which information belongs together and therefore affect the resulting requirements.

FEV therefore uses a controlled workflow: rules provide repeatable coverage, while AI agents handle language and contextual interpretation.



2
Before any requirements are generated, the regulatory document is decomposed and transferred into an explicit document model.

Structure before generation

The FEV Regulation Analysis Assistant (RAA) organizes the work in three phases. Each phase creates an intermediate artifact that can be inspected, stored, and reused.

First, the document is decomposed. The system builds a tree of chapters, sections, and paragraphs before the raw text is assigned to its nodes. Figures and tables are extracted with positions and captions. References to other sections and artifacts are identified. Rules check whether page ranges and parent-child relationships are consistent, while dedicated agents retrieve relevant pages and propose and verify corrections. The result is an explicit document model.

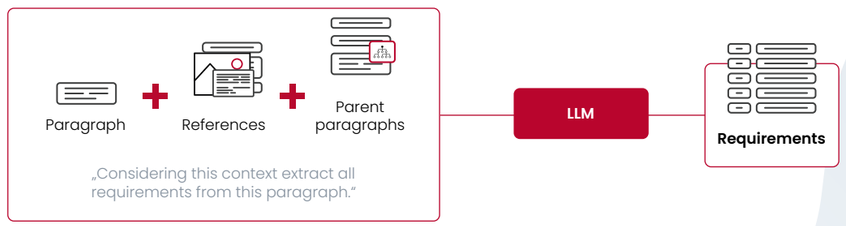
Second, RAA creates a context package for every paragraph. It contains the local text, summaries of parent sections, associated figures and tables, and resolved references. External passages can be retrieved from a connected regulatory database. The resulting context package supplies the information needed for one section without placing the entire document into every prompt.

In the final step, requirements are generated section by section. The prompt combines the prepared context with the selected system scope and output schema. Because generation follows the hierarchy, every section can be processed exactly once. The work can also be parallelized, since each context package is self-contained. This hybrid design is important: deterministic orchestration establishes coverage and repeatability; the LLM translates normative language into engineering-oriented statements.

The selected scope matters. A regulation also contains obligations for authorities, test services, or other actors that may be irrelevant to an OEM or supplier. Explicit filters and metadata help the generator focus on the requested system and stakeholder instead of returning every normative sentence it encounters.

The intermediate artifacts also make the process adaptable. Engineers can regenerate output for another subsystem, stakeholder, or template without repeating document ingestion. They can inspect hierarchy and context independently of the wording, exposing errors earlier than a black-box step would.

3
RAA reconstructs the document, builds section-specific context, and generates requirements with linked evidence.



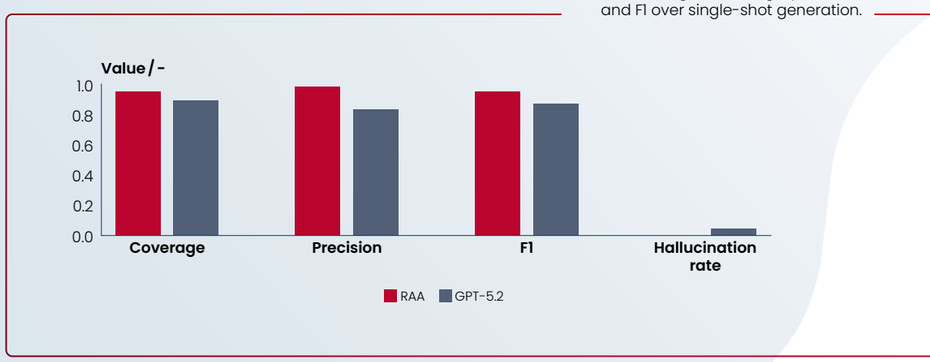
Traceability by construction

Traceability is most valuable when created with the requirement, not reconstructed later. The RAA stores the originating document node and supplied evidence alongside every statement: document version, clause, page, table, or figure, referenced passage, and an internal reference ID. Consider an on-board monitoring system in an M2 vehicle that must register NOx, NH_3, and particulate-matter emissions. The local clause defines the obligation but points to categories and limits elsewhere. The RAA resolves these links before generation and records them along with the result. An expert can move from the engineering statement to its exact evidence and review the interpretation. By following this approach, the evidence chain supports more than an audit. When a new version changes or relocates a clause, the structured representation also helps identify affected requirements. Additionally, one broad obligation may become several atomic, testable requirements. More output is not more noise if every statement is relevant, actionable, and grounded.

Evidence from Euro 7

FEV evaluated the RAA using Regulation (EU) 2024/1257, commonly known as Euro 7, focusing on emissions monitoring, anti-tampering, and state of health. To assess the benefit of the structured workflow independently of the underlying language model, its results were compared with a single-shot GPT-5.2 baseline using the same LLM. FEV domain experts established a reference set tailored to the relevant OEM and Tier-1 scope, while the generated outputs were anonymized and randomized before being assessed as correct matches, irrelevant statements, or unsupported content. The results are summarized in Figures 4 and 5.

4
In three Euro 7 domains, RAA improved macro-averaged coverage, precision, and F1 over single-shot generation.



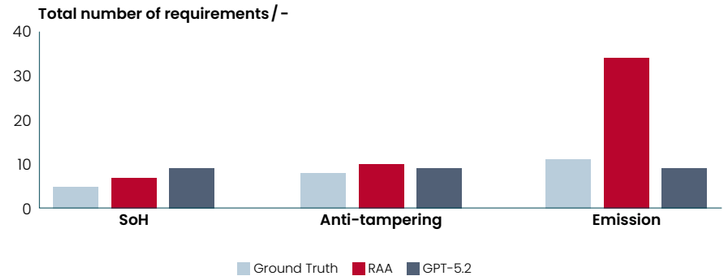
»More output is not more noise if every statement is relevant, actionable, and grounded.«

Across the three domains, RAA achieved 97.2% recall, 99.0% precision, and an F1 score of 96.9%, compared with 89.2% recall, 84.7% precision, and an F1 score of 86.4% for the single-shot baseline. Moreover, none of the RAA outputs were classified as hallucinations in this evaluation. The benefits were particularly evident in emissions monitoring, where RAA captured the complete reference set, including obligations concerning access to current pollutant information and the detection of malfunctions leading to emission exceedances. In the anti-tampering domain, it generated a more focused set with fewer irrelevant statements. RAA also translated broad regulatory obligations into smaller, engineering-oriented units that can be allocated and verified more effectively. Although this increased the number of statements – especially for emissions monitoring – it did not simply add irrelevant content. The results therefore underline that extraction quality should be assessed through coverage, relevance, grounding, and engineering usability rather than output quantity alone.

From extraction to an engineering workflow

These structured requirements and evidence can populate a searchable database with source, version, clause, jurisdiction, vehicle type, system of interest, and review status. Instead of another project spreadsheet, teams gain a reusable knowledge base for filtering product scopes, comparing markets, and supplying downstream development. The same foundation supports further AI-assisted steps. Review agents can check ambiguity, duplicates, inconsistencies, and writing guidelines. Analysis agents can compare sets or answer questions with source links. When a regulation changes, version comparison and trace links focus attention on affected obligations and engineering artifacts.

Because the framework and contexts are preserved, the organization does not need to start from the original PDF for every downstream question. One validated ingestion can support tailored requirement sets for multiple vehicle categories or systems. It can also provide a common evidence layer across legal, engineering, and verification teams, reducing the risk that each function maintains its own interpretation of the same clause. The useful architecture is not a standalone chatbot but connected services in the requirements-engineering toolchain. Each receives the information it needs and produces an inspectable artifact for the next step.



5
Quantity of generated requirements compared to expert ground truth.

BY
Dr.-Ing. Lukas Schäfers
schaefers_luk@fev.com
Fabian Schmidt
schmidt_fa@fev.com
Dr.-Ing. R. Savelsberg
savelsberg@fev.com

Conclusion

AI support does not transfer responsibility for compliance to a model. Experts still decide scope, resolve ambiguity, assess feasibility, and approve requirements. Its value lies in changing where experts' time is spent. Instead of searching page by page and documenting provenance manually, engineers review evidence-backed candidates and concentrate on decisions that need their expertise. The process becomes easier to repeat, audit, and update. "Requirements at a click" is not a black box that replaces judgment. Behind the click is a controlled chain of document reconstruction, context building, AI interpretation, traceability, and expert approval. Making that chain visible turns generative AI into a dependable engineering assistant.

We are close to our customers with **45 locations globally**

FEV Europe GmbH
Neuenhofstraße 181
52078 Aachen
Germany
P +49 241 5689-0
marketing@fev.com

FEV North America, Inc.
4554 Glenmeade Lane
Auburn Hills
MI 48326-1766 USA
P +1 248 373-6000
marketing@fev-et.com

FEV China Co., Ltd.
168 Huada Road
Yanjiao High-Tech Zone
065201 Sanhe City
Langfang Hebei Province
China
P +86 10 80 84 11 68
fev-china@fev.com

FEV India Pvt. Ltd.
Technical Center India
A-21, Talegaon MIDC
Tal Maval District
Pune 410 507 India
P +91 2114 666-000
fev-india@fev.com

RECYCLED
Paper made from recycled material
FSC™ C106855
FSC www.fsc.org

SPECTRUM #84
Issue 03/2026

Editorial
Marius Strasdat

Layout
Verena Mainz

FEV Global Marketing & Communications

Reader service
Would you like to receive future issues of SPECTRUM, or has your mailing address changed? Please send your name, company name, and mailing address to **spectrum@fev.com.**

company/fev-europe

feel evolution



fev.com