#82

SPECTRUM

Optimizing vehicle-to-grid ecosystems with AI **P. 06**

REEV – Bridging the gap in heavy-duty electrification **P. 14**

FEV eDLP – Certified testing for performance, safety, and compliance **P. 30**

From diesel to ammonia – CO_2-reduced commercial propulsion **P. 44**

Dear readers,

At FEV, we advance innovation across industries — from aerospace via automotive to rail and marine as well as energy & resources. In this issue of SPECTRUM, we highlight how our development in propulsion and electrification is bridging boundaries, driving cross-industry progress, and shaping the future of mobility and energy worldwide.

The transition toward climate-neutral propulsion is accelerating – yet the technological pathways remain diverse. Different applications, infrastructures, and regional conditions require different solutions. As a result, the future of propulsion will not be defined by a single drivetrain concept, but by a portfolio of technologies that must work reliably in real-world applications.

One particularly interesting example is the role of range-extended electric vehicles (REEVs) in heavy-duty transport. While battery-electric trucks represent the long-term target for zero-emission logistics, infrastructure rollout and operational constraints still pose challenges in long-haul applications. REEV concepts can bridge this transition phase by enabling near zero-emissions operation with significant range.

At the same time, advances in battery intelligence and testing are strengthening the technological foundation of electrified propulsion. In this issue, we explore how AI-enabled digital battery twins support earlier fault detection and predictive diagnostics, and how certified testing facilities such as FEV's eDLP help ensure the safety and reliability of modern battery systems.

Beyond road transport, the transition toward climate-neutral propulsion is also gaining traction in other sectors. Hydrogen-based fuel cell systems are opening new opportunities for rail applications, while ammonia-fueled engines are emerging as a promising pathway for reducing emissions in maritime propulsion.

Together, these contributions illustrate how engineering expertise, system integration and cross-industry experience are shaping the next generation of propulsion systems. Ultimately, progress toward sustainable mobility will depend not on a single technology, but on the ability to combine and integrate multiple propulsion concepts into robust and scalable solutions.

Enjoy the read!

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

CONTENT

#1

Optimizing ***vehicle-to-grid ecosystems*** with AI-driven simulation

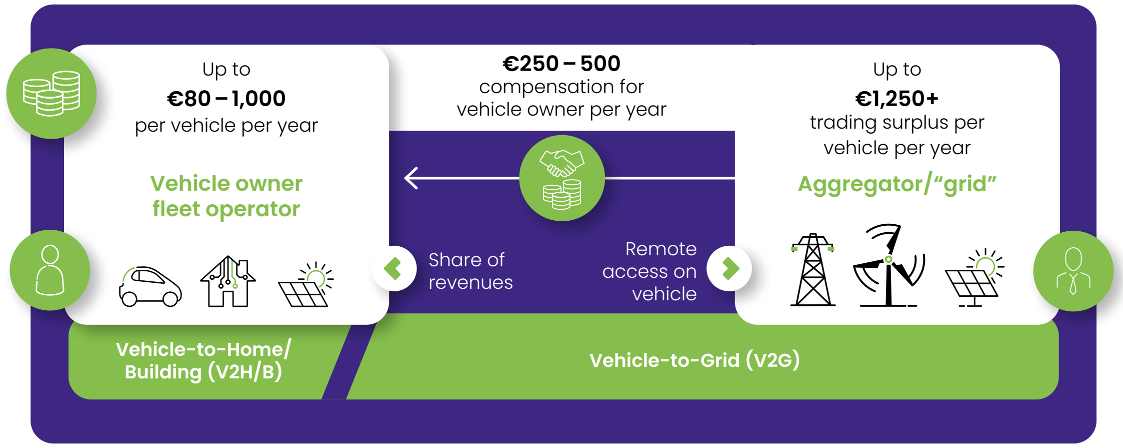
As electric vehicles (EVs) become part of larger energy systems, the question for operators is no longer simply how to charge them – but how to turn them into economic assets. Bidirectional charging enables EVs to support buildings, fleets, and even the power grid; creating new revenue streams and reducing energy costs. FEV's Vehicle-Ecosystem Twin (Vynox) simulates and optimizes the interaction between vehicles, charging infrastructure, buildings, and the grid. As such, it supports individual vehicle owners, as well as fleet operators, to investigate the concrete revenue of vehicle-to-grid (V2G) for their use-case.

Why V2X matters for energy systems

The promise of bidirectional charging is straightforward: EVs are mobile, distributed batteries. With bidirectional onboard chargers, they can help shave power peaks, absorb photovoltaic (PV) surplus, arbitrage between off-peak and on-peak electricity prices, as well as support frequency services where markets allow. Vehicle-to-Home/Building (V2H/B) acts behind-the-meter and reduces the electricity consumption of the house or building in times of high-power demand or high electricity prices. V2G is grid-facing and goes one step further by injecting current behind the meter to profit from energy arbitrage.

In some countries, V2G already supports ancillary services by grouping EVs and further energy assets into a virtual power plant to meet the mandatory power and energy criteria. Drivers are compensated via an energy contract, effectively turning their vehicles into revenue earning grid assets, orchestrated by an aggregator. Whether V2H or V2G delivers the greater benefit depends heavily on each site's mobility patterns, price structures, and regulatory environment, and must therefore be evaluated on a case-by-case basis.

The experts at FEV energy + resources are specialized in consulting and engineering to deliver holistic solutions to our customers. With more than four decades of expertise FEV energy + resources integrates decarbonization strategies and technologies with a viable resource management approach. Tailor-made, cost-efficient and sustainable – both for the customer and our environment.



1
Profit range for vehicle owners operating their own V2H/B strategy compared to V2G being orchestrated by an aggregator for ancillary services.

From vehicles to energy assets

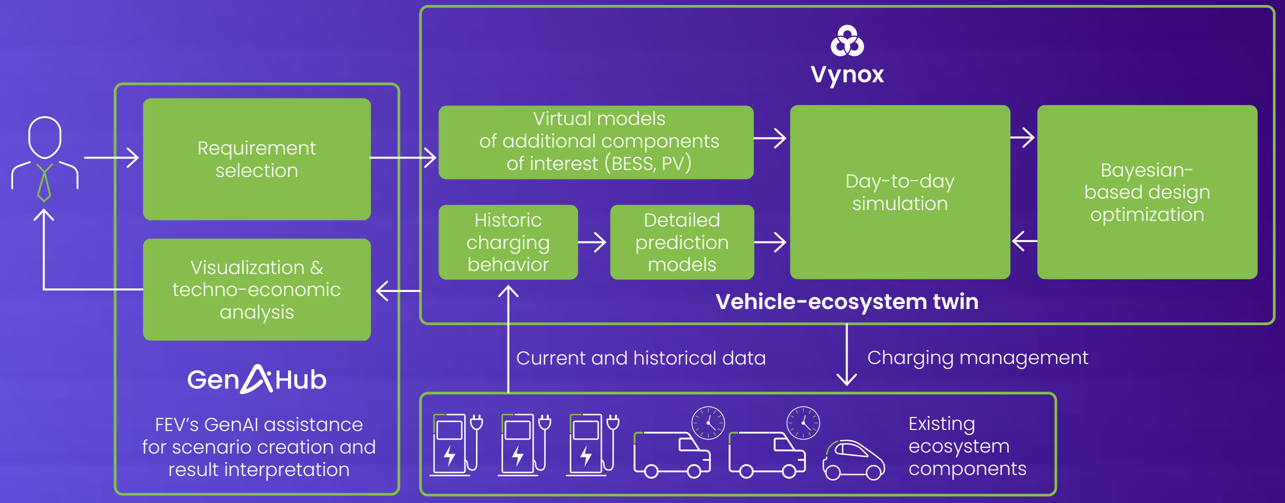
Even if V2G already exists in some markets, the reality is still complex: Electricity markets differ across regions; price structures range from flat and time-of-use schedules to fully dynamic pricing and eligibility criteria for demand response or frequency services vary. Success depends as much on the technology as it does on the local regulatory boundaries and local conditions, considering the end user's mobility needs. Thus, succesful V2G operation not only depends on the vehicle itself but on how the entire ecosystem around it behaves. Optimizing a single car or charger in isolation therefore misses most of the value. Real value emerges only when vehicles, chargers, stationary storage, and local generation are controlled as a coordinated system across the entire site or fleet.

Relevance for OEMs and fleet operators

V2G will only scale if customers trust the business case. Demonstrating where bidirectionality creates value, by quantifying savings or peak reductions, helps accelerate adoption. For fleet and mobility operators, rising energy costs and growing depot complexity necessitate decisions that are both technically sound and economically proven. If decisions are made with static tools and idealized assumptions, companies misallocate capital by installing wrong assets, overbuilding grid connections, or waiting in vain for the approval of the grid connection. The ability to test "what if" configurations without disrupting operations helps make the right investments within specific boundaries and shortens payback periods.

FEV's answer: Vynox, a cloud-native toolchain built for decisions

Vynox, FEV's Vehicle-Ecosystem Twin, begins with your real site and market conditions rather than a one-size-fits-all template. It encodes country-specific grid rules and links your existing assets with virtual ones in one simulation with an electricity price-aware, optimization-ready Energy-Management-System (EMS) that respects mobility needs. Validation in simulation before deployment lets you incorporate custom requirements and stress-test edge cases. The end-to-end toolchain unifies a cloud-native framework that builds the VE Twin from operational data, an EMS that runs seamlessly in simulation and in operations, and a final layer that tests different configurations and converts simulation results into a comprehensive techno-economic evaluation.



2
Vynox toolchain.

Turn operational data into optimized charging strategies

The connection of assets to Vynox is realized through industry standard protocols, so onboarding is fast and vendor agnostic. The system ingests historical charging sessions and site loads, aligns them with energy price signals, and compiles a record of how energy flows through the depot or facility, where your cars are charged.

Where explicit arrival and departure times are missing, the platform generates predictions based on the collected historical data using Long Short-Term Memory (LSTM) neural networks. With these inputs, the EMS computes an operational charging strategy in real-time. Operators can emphasize different objectives: lower energy cost, reduced peak load, or maximized use of renewable energy. The optimization framework also considers battery usage constraints, ensuring that V2X operation remains within acceptable degradation limits defined by the operator.

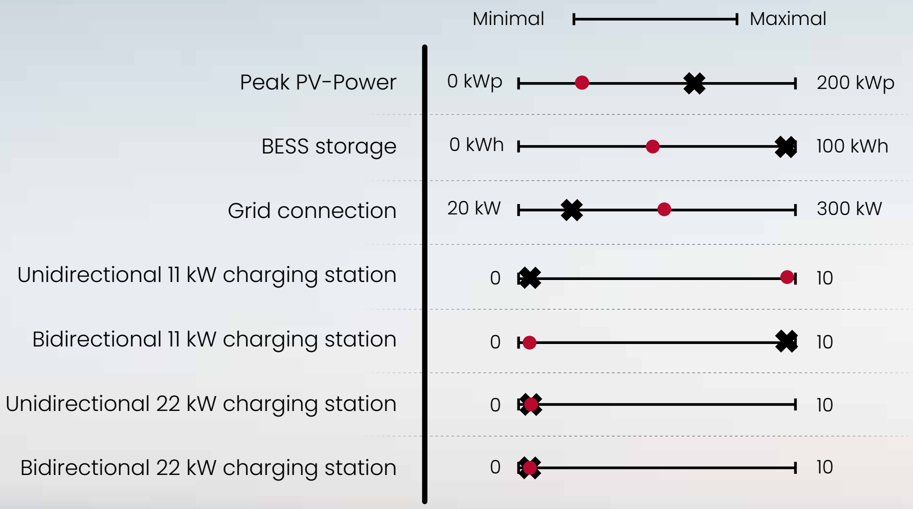
Planning infrastructure investments with simulation

The real power of Vynox appears when planning expansions. Within the same environment, operators can add virtual energy components. These may include additional charging stations with different power levels and bidirectional capability, new PV capacity, or a battery energy storage system (BESS). Operators can then test these components against their current vehicle usage profiles.

What emerges is a comparison of possible electricity contracts, frequency-market use cases, and possible configurations considering the assets that are already present. In other words, you evaluate options the way they will be used, not the way a spreadsheet assumes they might be. One highlight of the VE-Twin is the use of Bayesian Optimization (BO), replacing brute force design scans and converging to the best configuration in a fraction of the iterations typical for Design of Experiments; while honoring grid limits, charger ratings, and investment caps. Edge and worst-case conditions are tested upfront, leading to right-sized energy components rather than static buffers. The results are directly translated into CAPEX/OPEX views, peak charge exposure, and onsite renewables share, with multi-year sensitivity to electricity price and tariff shifts or energy market changes.

Remove friction with FEV's GenAI assistant

Investment projects often begin with incomplete information. To keep momentum, the platform includes a conversational assistant that interviews users about missing inputs (for example, typical arrival patterns, weekend behaviors, or the usable window of a BESS) and fills gaps with consistent defaults that can be refined later. Beyond discrete choices, decision makers can enter permissible ranges for variables such as the number of new charging points, available roof or lot area for PV charging, or the maximum investment budget. This accelerates the



3
Start configuration and result of the Bayesian Optimizer for the fleet depot use-case.

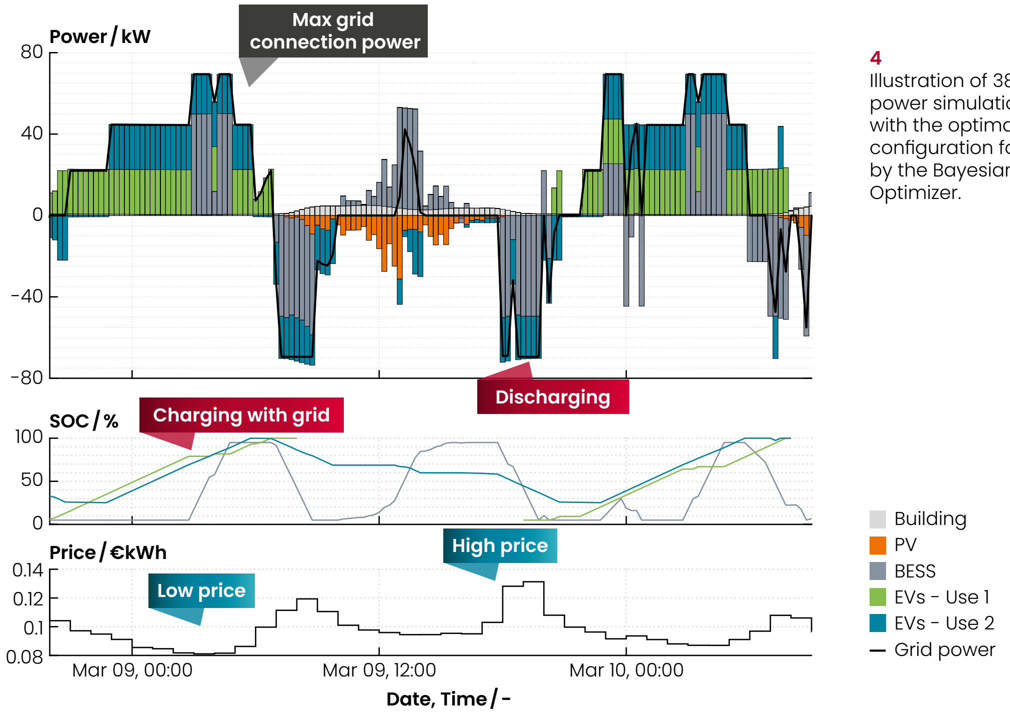
time to first simulation and makes advanced workflows accessible for non-specialists.

Use-case: Fleet depot expansion with V2G
The business impact becomes concrete in a fleet depot study. For a small rental operator wanting to acquire ten battery electric vehicles, the question arises whether bidirectional charging stations with a dynamic price could reduce his electricity costs. Vynox ingested a month of existing vehicle telematics, the local site consumption of the rental operator, budget and sizing limits, and regulatory boundaries of the grid provider.

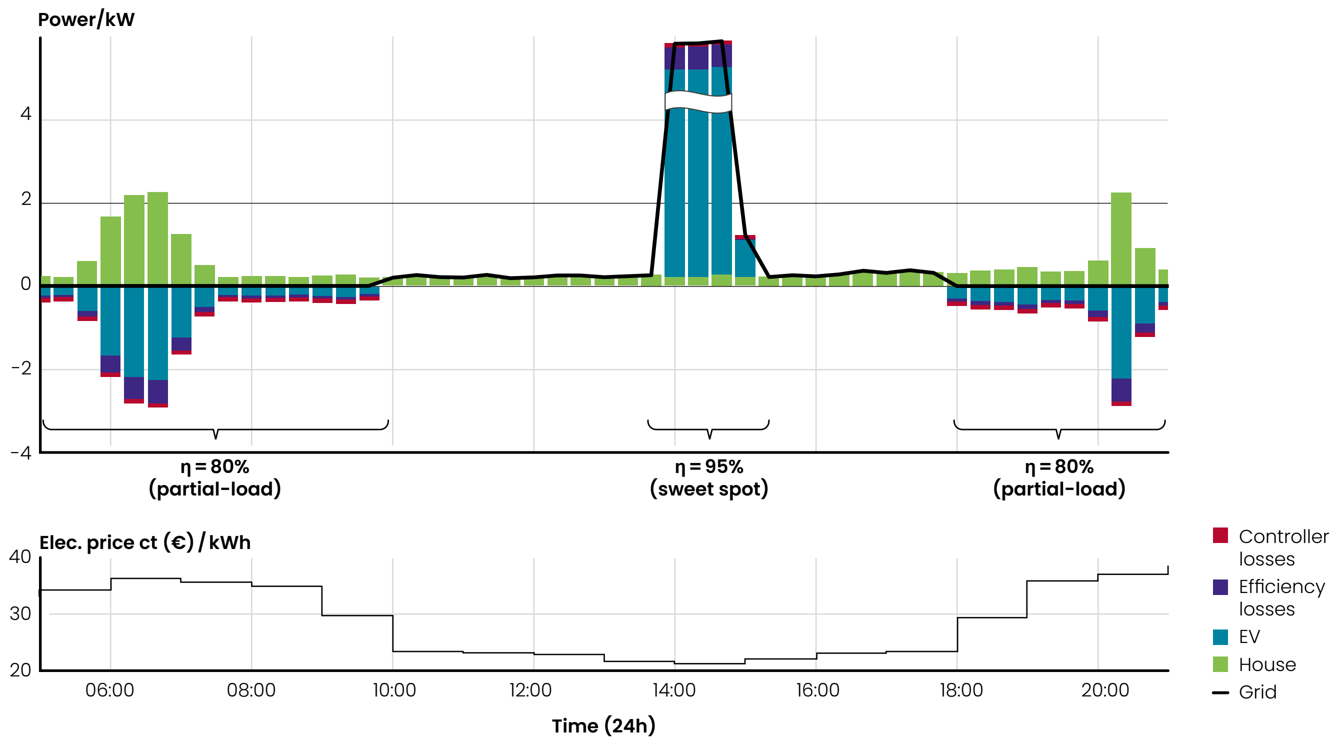
The optimum found by the Bayesian Optimizer is shown in Figure 3. It favored ten 11 kW bidirectional chargers, 134 kWp of PV, 99 kWh of BESS, and a grid connection of 69 kW. The analysis ran roughly 120 times faster than a comparable Design of Experiments scan, and demonstrated how coordinated assets and a right-sized grid connection reduce both peak loads and operating costs without compromising service levels. The analysis showed that bidirectional charging stations are profitable, but 22 kW charging stations are unfavorable compared to a larger BESS, due to mostly overlapping EV standing times and the ability to limit grid connection power.

For each of the configurations tested by the BO, one year of operation was simulated, and the controllable loads were optimized using the integrated EMS. An exemplary section of the EMS simulation with the best configuration is shown in Figure 4.

The stacked bars in the upper plot showcase the component-level power flows in 15-minute intervals, as well as the resulting grid power, while positive values indicate power consumption and negative values indicate supply. During the low price windows shown in the bottom plot, the EMS charges the BESS and vehicles from the grid and PV, pushing the grid import up to the connection limit, resulting in an increase of the state-of-charge (SoC), as showcased in the middle plot. During high price windows, the EMS covers the building demand with a coordinated discharge from the BESS and EVs, driving grid power negative while still respecting the grid connection power limit and ensuring the vehicles are charged to 100% SoC when they are leaving.



4
Illustration of 38-hour power simulation with the optimal configuration found by the Bayesian Optimizer.



5
Exemplary results of the EMS in the V2H use case.

Use-case: V2H for private household

Vehicle-to-Home can be assessed with the same rigor. With a month of household consumption, typical arrival and departure times, and local day-ahead-prices, homeowners can simulate an annualized cost view that reflects their specific profile before committing to a bidirectional charger. An exemplary extract of an EMS simulation is shown in Figure 5, including controller losses and charging session efficiency under different power levels. The EMS discharges during expensive morning and evening periods to maintain a net-zero electricity consumption at the household level and recharges during low cost times during the day.

For the chosen scenario, the realized electricity cost reduction with a bidirectional charger was about €80 per year. If efficiency and controller losses were ignored, €380 per year would have been achievable, highlighting the importance to considering losses when modeling V2X business cases. For this specific use case, two possibilities can be considered: investment in a charger with higher partial-load efficiency and lower standby draw, or the addition of a small stationary battery as a buffer so the charger runs for a shorter duration and in its most efficient operating range. Both variants, their sensitivities to efficiency curves and standby power, as well as the techno-economic optimal configuration can be evaluated in minutes with Vynox.

BY

Nicolas Rößler
roessler@mmp.rwth-aachen.de

Feihong Xia
xia_f@fev.com

Christoph Wellmann
wellmann@mmp.rwth-aachen.de

Rene Savelsberg
savelsberg@fev.com

Johannes Buchmann
buchmann@fev.com

> »Bidirectional charging enables EVs to support buildings, fleets, and even the power grid, creating new revenue streams and reducing energy costs.«

Conclusion

V2X is not a one-size-fits-all proposition. Whether V2H or V2G delivers superior value depends on mobility patterns, price structures, regulatory constraints, and the assets already on site. Maximizing benefit requires orchestrating the entire ecosystem rather than optimizing a single vehicle, charger, or battery in isolation. Conventional planning approaches based on static assumptions or spreadsheet models often overlook these interactions and therefore underestimate the economic potential of coordinated energy management. Vynox, FEV's Vehicle Ecosystem Twin addresses this reality by grounding the analysis in your operational data, coupling it with an optimization-ready EMS, and translating technical choices into CAPEX/OPEX and revenue impacts. It explicitly quantifies sizing trade-offs for PV, BESS, charger power, grid connection size, and V2G reserves against cost, power peak exposure, and component degradation. Thanks to the FEV GenAI assisted result interpretation, customers can pick the V2X strategy that is both technically feasible and economically sound today, and adapt as rules and the ecosystem evolve. For operators, the key question is no longer whether V2X creates value, but where and under which conditions it does. By combining operational data, AI-based prediction, and techno-economic optimization, Vynox enables evidence-based decisions before investments are made.

Heavy-duty fleets must decarbonize without compromising utilization or schedule reliability. In long-haul operations, missed charging windows, grid-connection lead times, or uneven corridor coverage can quickly turn a purely battery-electric vehicle concept into an operational risk.

Battery-electric trucks (BEVs) are the preferred choice wherever dependable depot and corridor charging is available. Yet in many regions, charging rollout and grid access remain uneven – particularly along long-haul routes.

In Europe, policy accelerates both vehicle and infrastructure timelines. CO_2 standards are tightening toward 2030 and 2035, while AFIR requires publicly accessible heavy-duty charging pools on the TEN-T core network, up to 60 km apart in each travel direction by 31 December 2030. Commission reporting highlights grid access as a primary bottleneck for reliable corridor high-power charging operations.

In the near term, most energy will still be supplied during and overnight windows, and corridor charging will scale lane-by-lane as grid and permitting constraints are resolved. The Megawatt Charging System (MCS) aims to enable >1 MW-class charging for heavy-duty applications and is being specified and industrialized across the ecosystem.

#2

REEV – Bridging the gap in ***heavy-duty electrification***

In this transition window, BEV-derived range-extended electric vehicles (REEVs) can provide a regulatory-compliant method to protect utilization. They retain electric traction and add an on-board generator to hedge against incomplete or delayed charging. This article compares BEV, REEV, and PHEV concepts for a representative 40-t tractor-trailer using utility-factor logic for certification-relevant TTW CO_2, complemented by a WTW perspective. Results depend strongly on energy prices, charging conditions, and incentive parameters.

Key terminology

- BEV: Battery-electric vehicle, purely electric traction
- REEV: BEV-derived range-extended electric vehicle with on-board generator (no mechanical ICE-to-wheel connection)
- PHEV: Plug-in hybrid electric vehicle with charge depleting and charge-sustaining operation
- UF (Utility Factor): Share of operation in charge depleting mode used for certification weighting
- TTW / WTW: Tank-to-wheel (vehicle tailpipe) vs. well-to-wheel (full energy chain)

Use-case and powertrain topologies

To understand where REEV adds value, the analysis first maps relevant heavy-duty mission profiles and technology concepts. The analysis is anchored on a 40-t tractor–trailer and models EU long-haul and regional missions using representative state-of-charge (SoC) windows, dwell patterns, and grade profiles. The logic can by applied to other regions if daily mileage, ambient extremes, and charging access are adapted.

Figure 1 frames the mission space by average daily distance and motivates a split into short-distance, hub-to-hub, and long-distance operation. For Alpine transits, internal simulation indicates a ~30% beginning SoC to match a diesel speed envelope, and avoid prolonged charge-sustaining exposure. BEV and REEV capability bands overlap. In this overlap, REEV hedges charging timing, availability, or grid-access uncertainty.

Figure 2 summarizes the topology classes and main component sets. PHEV uses an externally chargeable mid-size HV battery to provide a defined charge-depleting range, followed by charge-sustaining operation. Depot-centric charging is assumed, and certified CO_2 is expressed through utility-factor weighting. REEV denotes an externally chargeable, BEV-derived series architecture without a mechanical ICE-to-wheel connection. A mechanically decoupled generator set supplies the high-voltage direct-current link (HV-DC link) as a dispatchable on-board energy source.

"REEV-light" (~120–130 kW continuous) and "REEV-strong" (≥150–200 kW continuous) represent variants from occasional range extension to continuous-duty stabilization. The BEV relies on the HV battery as the only on-board energy storage and manages constraints through battery sizing, thermal limits, and charging planning. Terminology and UF framing align with published definitions.

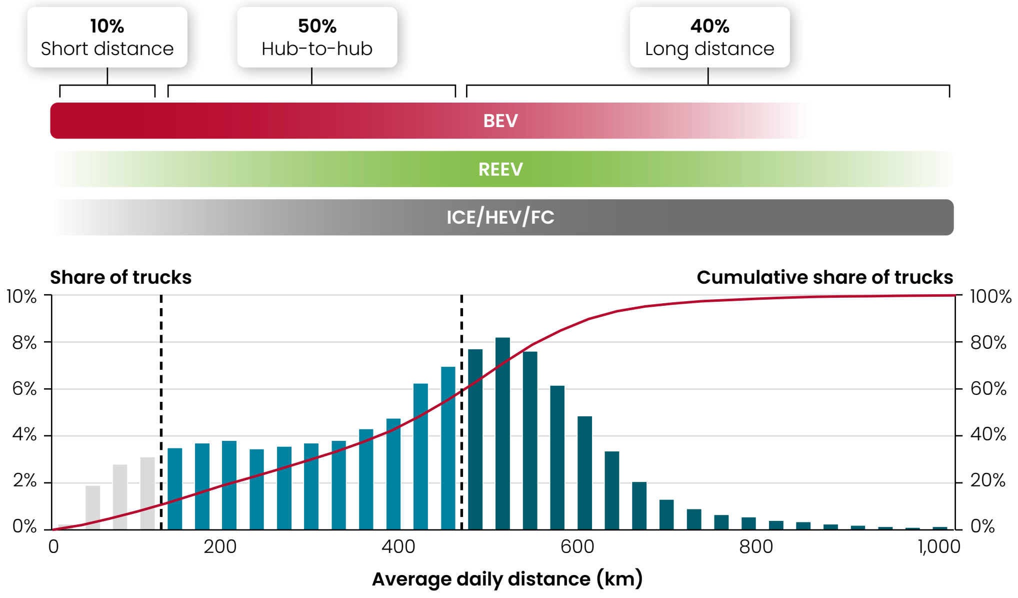
Why utility factor (UF) determines certification outcomes

Under corridor charging constraints, BEV, PHEV, and REEV concepts are compared using certification-relevant TTW CO_2. REEVs trade battery capacity for an added genset to protect utilization when charging is uncertain.

In VECTO, the utility factor (UF) weights charge-depleting (CD) and charge-sustaining (CS) operation in certified TTW CO_2. With $CO_2CD = 0$, high UF becomes the key certification driver for REEVs:

$$CO_{2\,\text{weighted}} = CO_{2\text{CD}} \times UF + (1-UF) \times CO_{2\text{CS}}$$

In short, certified TTW CO_2 depends mainly on how often the vehicle can operate in charge-depleting mode under real charging conditions.



1
Split of EU heavy-duty tractor missions by average daily distance, with indicative technology fit bands for BEV, REEV, ICE/HEV/FC (based on ICCT and European Commission).

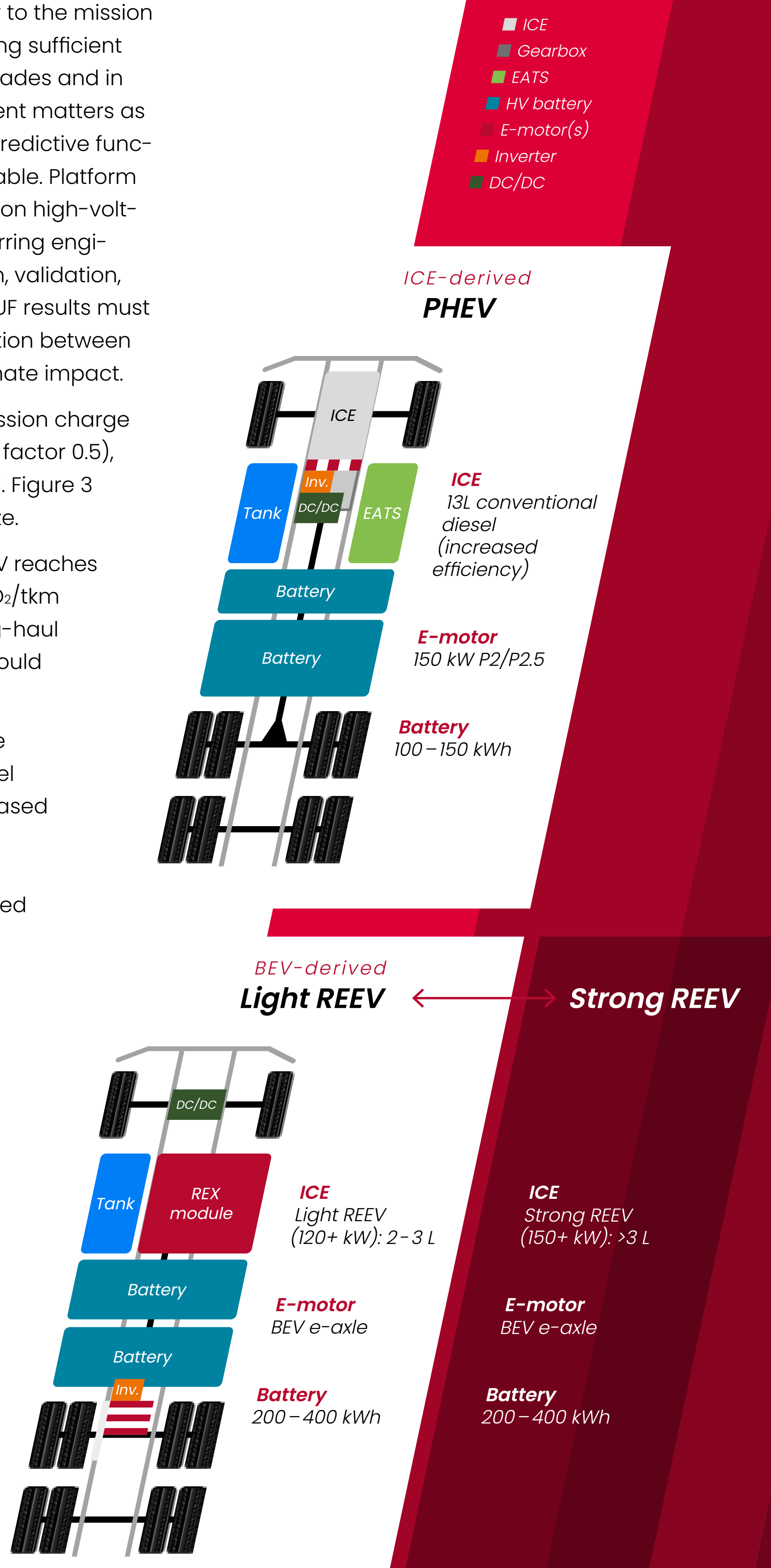
In practice, UF is driven by charging reality, meaning depot power, corridor access, and available dwell time. It also depends on right-sizing the battery to the mission rather than the worst case, and on ensuring sufficient continuous power to avoid derating on grades and in hot conditions. Robust energy management matters as well, with rule-based strategies first and predictive functions added only when data quality is reliable. Platform reuse can increase UF by enabling common high-voltage components and reducing non-recurring engineering (NRE) and "integration, verification, validation, and qualification" (IVVQ) effort. However, UF results must always be interpreted with a clear distinction between TTW certification outcomes and WTW climate impact.

In the VECTO parameter study (one in-mission charge per day, 0.5 h window, 500 kW cap, usage factor 0.5), UF rises with charging power until capped. Figure 3 shows the sensitivity versus the battery size.

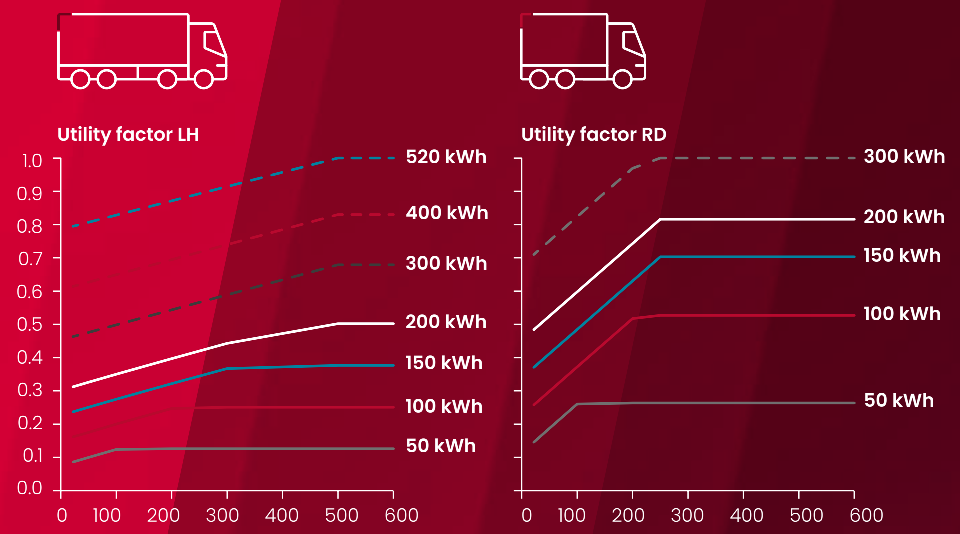
Selected results: a 200-kWh long-haul PHEV reaches UF = 0.502 and CO_2-weighted = 23.61 g CO_2/tkm (baseline 50 g CO_2/tkm). A ~400-kWh long-haul REEV reaches UF ≈ 0.83 at 500 kW; UF = 1 would require ~880 kW.

VECTO reports TTW CO_2 only and therefore does not reflect upstream electricity or fuel pathways. For climate impact, add JEC-based WTW overlays with defined electricity and fuel pathways. Time-varying grid intensity should be stress-tested using time-resolved datasets.

The relevant question is not peak UF in a single scenario, but how robust UF remains under imperfect charging conditions. In the following, the focus is on the engineering levers behind product-ready HD-REEVs.



2
Topology overview and main components (PHEV/REEV-light/REEV-strong/BEV) with illustrative concept specifications, FEV analysis.



3
UF for different battery capacities for long haul truck (LH) and regional delivery (RD).

What makes an HD-REEV product-ready

HD-REEVs become become product-ready only if efficiency and thermal robustness are maintained in continuous duty. The key levers are battery right-sizing, a continuous-duty generator unit, and a validated platform architecture across HV, charging, thermal, and controls.

Battery system

HD-REEV batteries are sized for electric share under corridor constraints, not for worst-case range. The genset stabilizes operation on grades and during high-speed cruising, while the battery buffers transients and enables extended electric operation where charging is available.

The choice of chemistry and pack design must account for frequent charging and sustained power demand. LFP/LMFP offers cost-robust characteristics, whereas higher-energy chemistries can reduce mass but tighten thermal and aging margins. Voltage level and charging assumptions must be defined together (including 800 V), otherwise late interface changes and increased validation risk may occur. Multi-loop cooling, together with coordinated derating, represent key feasibility requirements.

Power electronics, electric drive and generator

The system should be designed around the continuous operating region. SiC and higher torque-density machines can reduce losses and heat at duty-cycle operating points, but these benefits depend on thermal limits and packaging.

The genset closes sustained energy gaps and must be sized for continuous cruise and grade power, while the battery covers peak demand within SoC and thermal limits. Operation is constrained by NVH, emissions, and aftertreatment temperature; the HV-link interface determines machine and power-electronics efficiency. A key trade-off emerges at the DC link and inverter level: 400 V systems with IGBTs offer advantages in cost and maturity but require higher current levels, whereas 800 V systems with SiC reduce current and losses but increase EMI and insulation effort, and require thorough continuous-duty validation.

Industrialization is trending toward modular "power-in-box" units with standardized electrical and thermal interfaces, with variants primarily defined by power rating and calibration. Protection strategies, thermal limits, and diagnostic functions must be translated into verifiable requirements aligned with functional safety.

System integration

System integration defines the interfaces between the battery, the traction inverter and machine, and the generator set. These components share the HV DC link, while DC/DC converters supply low-voltage loads, and HV partitioning together charging-path choices directly define BMS, VCU, and thermal-controller interfaces, as well as IVVQ effort.

Charging assumptions define both the achievable electric share and the hardware limits. Corridor charging and top-up differ in predictability. MCS targets >1 MW-class heavy-duty charging, making electrical safety verification essential through measures such as insulation monitoring and clearly defined protection responses.

Thermal and EMC represent key feasibility requirements, with multi-loop cooling and coordinated derating managing coupled losses, while the DC-link layout and degraded-mode behavior must remain robust under fault conditions.

Robust online estimation of impedance, thermal headroom, and inverter safe operating area (SOA) helps manage aging effects and production variability in real operation. OTA-connected functions require development processes aligned with ISO 26262 and ISO/SAE 21434.

Controls and energy management

Energy management determines real-world results. Interfaces for DC/DC, OBC, and high-power charging define limits and diagnostics, while the genset must be controlled with respect to ramp rates, fault handling, and thermal limits.

To maximize UF, development should start with robust, rule-based power split, SoC windows, and start/stop logic, with preview-based charging planning and SoH-aware constraints added as data maturity increases. Predictive or MPC-based functions provide benefits when reliable preview information is available.

Coordinated thermal control prevents derating cascades and protects hardware, while statt and IVVQ should demonstrate robust interfaces, reliable diagnostics, and safety-relevant reactions. Predictive functions can be added as an optional layer, but they do not replace thorough system validation.

The content of this article was first published at the International Vienna Motor Symposium 2026.

Conclusion

BEV remains the preferred solution where charging infrastructure is dependable. However, during the current transition phase, charging rollout, grid access, and operational variability still limit pure battery-electric feasibility in many parts of the heavy-duty sector. BEV-derived REEV architectures offer a pragmatic bridge. By right-sizing the battery and adding a continuous-duty generator set, they preserve electric traction while protecting utilization against charging uncertainty. Certification outcomes depend strongly on utility factor, while real climate impact requires high electric share and low-carbon electricity. Results should therefore be stress-tested against charging assumptions, energy prices, and incentive frameworks.

FEV supports OEMs across this transition by combining vehicle-level simulation, powertrain development, HV system integration, and validation expertise. From concept benchmarking and VECTO-based CO_2 assessment to continuous-duty thermal design and generator calibration, the focus lies on delivering integration maturity rather than isolated component optimization.

Treated as a BEV derivative rather than a parallel platform, REEV can bridge uneven infrastructure rollout without abandoning electrified propulsion. With robust system architecture and validated controls, it becomes a scalable and industrially viable option for maintaining operational resilience during the ramp-up of heavy-duty electrification.

BY
Thomas Lüdiger
luediger@fev.com
Simon Dünnwald
duennwald@fev.com
Dr. Matthias Thewes
thewes@fev.com
Dr. Jan Nowack
nowack_j@fev.com
Dr. Rene Savelsberg
savelsberg@fev.com

#3

From fault detection to failure prevention – ***AI-enabled digital battery twins***

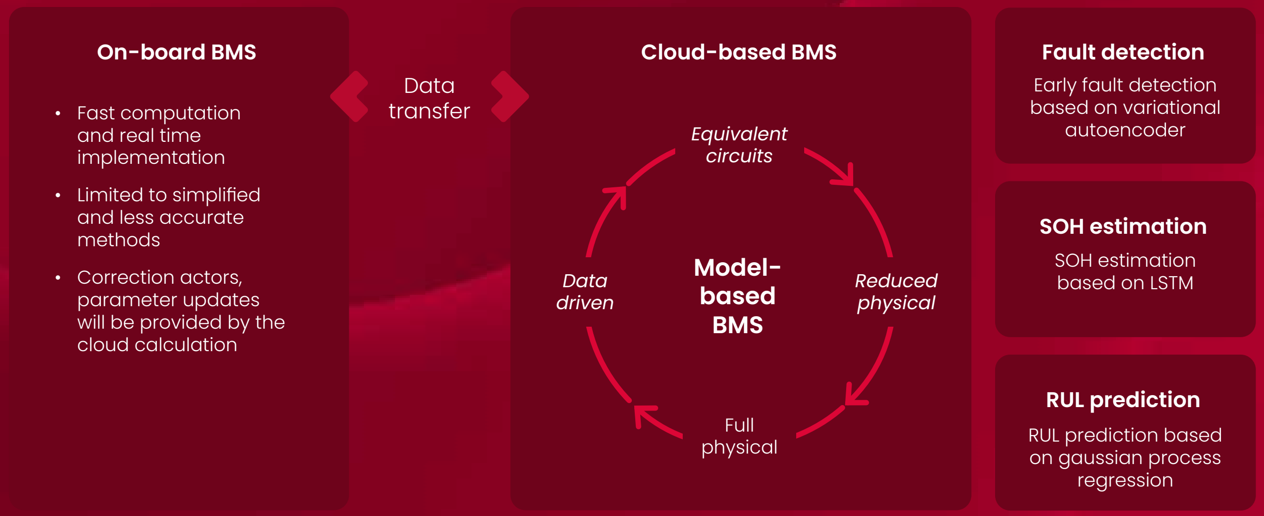
A single undetected cell fault can disable an entire battery pack – or in worst cases, trigger thermal runaway. As lithium-ion batteries move toward higher energy densities and tighter operating windows, early fault detection is no longer optional; it is a prerequisite for safe and economically viable electrification.

FEV addresses this challenge with a three-pillar safety strategy:

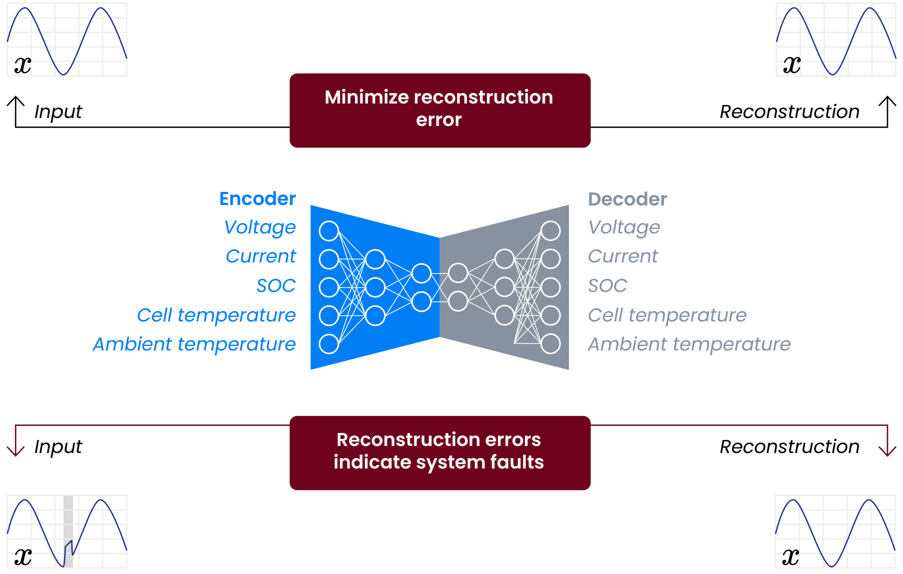
- Intrinsic safety of the cells
- Active safety by fault detection and mitigation
- Passive safety by design and testing

In this article, we focus on active safety and early fault detection. Detecting anomalies during their initiation phase enables interventions that prevent thermal runaway, avoid costly replacements, and preserve vehicle availability. FEV's digital battery twin shifts the focus from reactive, symptom-driven diagnostics to proactive, cell-level failure predictions designed to meet the safety and uptime demands of modern BEVs. For OEMs and fleet operators, this translates into reduced warranty exposure, improved fleet transparency, and measurable gains in vehicle uptime.

Cell-level early fault detection requires continuous sensing and characterization, and multi-physics models that link electrical, thermal, and mechanical signatures to early-stage failures. The combination of statistical anomaly detection and physics- based state estimation increases sensitivity to deviations while reducing false alarms. Machine learning models trained on accelerated aging datasets and on-line operational telemetry can detect complex, multimodal precursors that are invisible to single-parameter thresholds. Combining physics-based models with machine learning methods enables the detection of early-stage error indicators. To avoid "aging-as-anomaly" effects, models must account for baseline aging trends, such as SoH curves and temperature-dependent open-circuit voltages, and include explicit drift monitoring; otherwise, false alarms increase as fleets become more diverse.



1
FEV's BMS concept, including on-board side and cloud side.



2
FEV's anomaly detection concept based on VAEs.

The integration of early fault detection functions into digital battery twin systems requires advances in computationally efficient algorithms that work with fleet data. Real-time diagnostics require prioritizing interpretable measurement data that enable actionable mitigation strategies, such as balancing, cell isolation, derating, or planned maintenance. The validation of detection algorithms requires targeted fault injection, accelerated life testing, and field data collection under representative driving profiles to quantify detection lead-time, sensitivity, and specificity.

FEV's digital battery twin with its early fault detection reduces the number of vehicle failures, optimizes maintenance planning, and extends the usable battery life. The transition to proactive, physics-based diagnostics is both technically feasible and operationally beneficial, and represents a crucial step toward safer and more resilient electromobility.

For computational reasons and due to data availability, fault detection methods use model-driven, data-driven, or hybrid approaches. While most on-board algorithms rely on simplified models for real-time computations on limited resources, the trend toward digital twins enables data-driven and hybrid algorithms, unlocking the full potential of AI. AI-enabled digital twins transform BMS diagnostics into predictive maintenance systems due to their continuous monitoring of battery parameters such as internal resistance, voltage imbalances, and thermal gradients. By applying predictive analytics, fleet operators can detect early signs of cell degradation, connector corrosion, or thermal runaway risks. This allows for condition-based maintenance, reducing reliance on fixed service intervals, and minimizing unexpected breakdowns.

Unlocking hidden patterns with deep learning

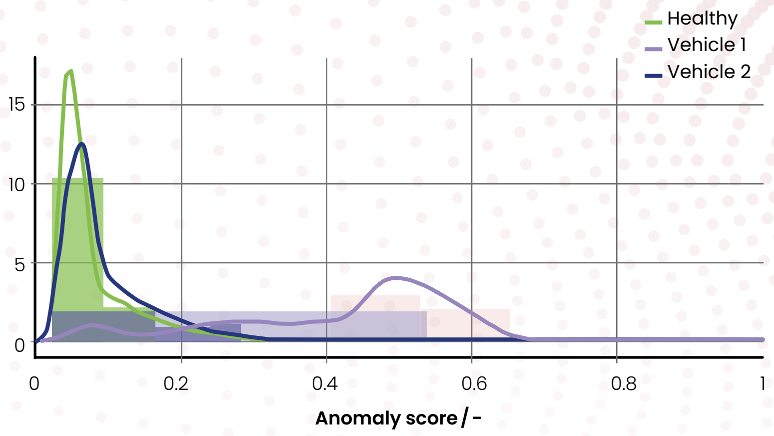
The tendency for increasing energy densities at lower costs motivates the desire to reduce safety margins while still maintaining safe operations. This trend increases the complexity of modern lithium-ion battery systems, particularly in electric vehicles and stationary energy storage devices. As a result, novel diagnostic procedures are required that are flexible, precise, and scalable. Purely data-driven methods can outperform simple thresholds on complex, nonlinear patterns but are sensitive to drift, coverage gaps, and label scarcity.

Data-driven approaches typically benefit from higher precision in complex data as they can identify nonlinear correlations and use pattern matching that remain hidden from traditional models. These approaches become scalable to different cell chemistries and operating conditions by providing suitable data sets for training.

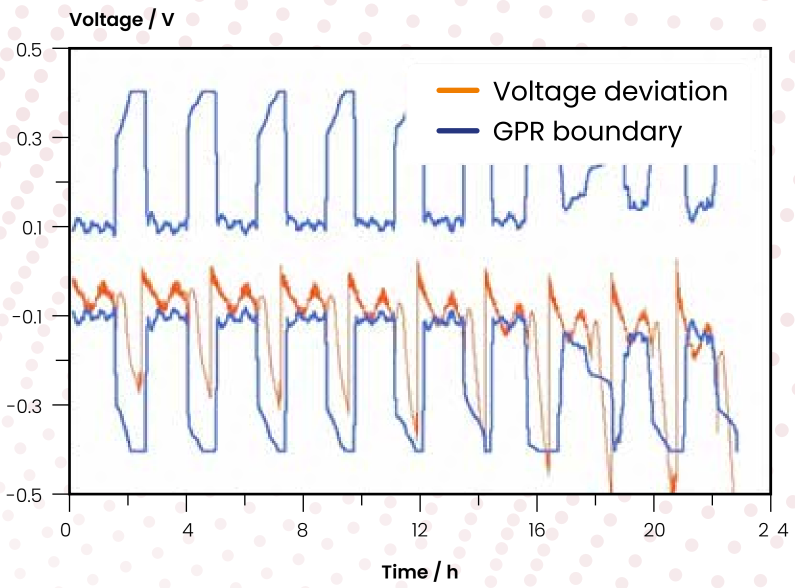
Figure 2 depicts FEV's concept for anomaly detection using the Variational Autoencoder (VAE). VAEs are AI models trained to translate complex data, such as BMS time series data, into a low-dimensional, “compressed” form. This compressed form is called the latent space. Unlike traditional autoencoders, VAEs work with probability distributions. This means they don't just generate a fixed representation of the data, but rather a “probability cloud” from which new, similar data can be generated. This enables VAEs to generate new, realistic-looking data (such as synthetic operating patterns that resemble real ones)and smoothly interpolate between different data points, while maintaining a good balance between accuracy and structure.

The VAE is trained exclusively with data from intact batteries, with the goal of minimizing reconstruction error. When runtime anomalies occur that were not present in the training data, the reconstruction error increases significantly. These deviations are used to analyze anomaly distributions within the vehicle fleet.

Figure 3 shows an illustration of possible VAE outputs used for anomaly detection. We use battery current, state of charge, cell temperature, cell voltage, and standard deviation of cell temperature and voltage as input signals. The VAE computes the anomaly score of the BMS data on the cloud. Comparing the anomaly score distributions of multiple batteries to an expected distribution, faults can be detected at an early stage.



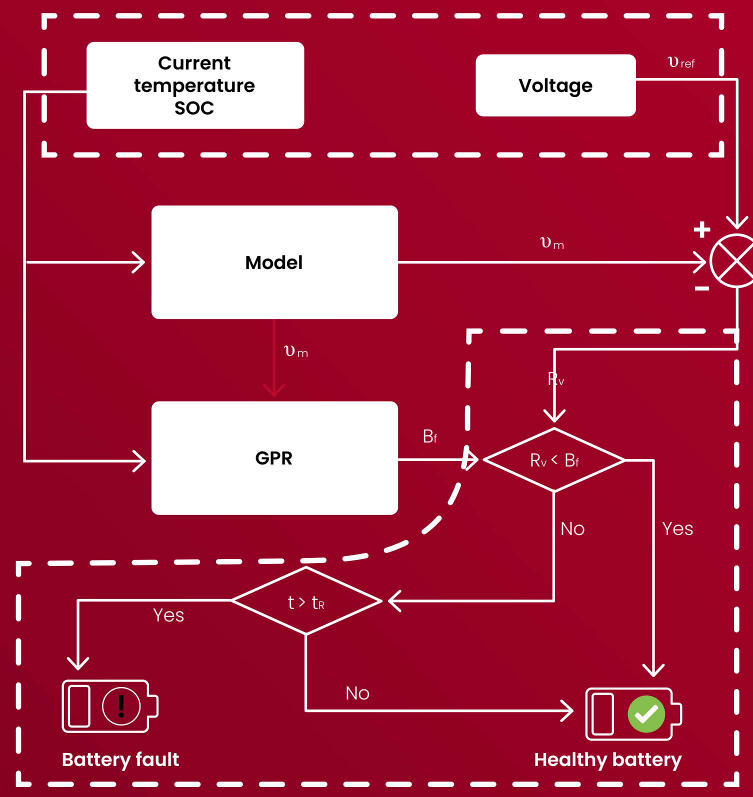
3
Anomaly score distributions derived by the VAE approach.



5
Results of the hybrid GPR approach.

Hybrid intelligence for safety-critical systems

Grey-box models combine domain-specific knowledge from physical or electrochemical battery models with the adaptability of data-driven methods. This allows them to combine the strengths of both approaches while compensating for their weaknesses. In safety-critical systems, such as in a BMS, this results in greater robustness, accuracy, and reliability than purely data- or model-based methods. Grey-box approaches benefit from better generalizability within new operating conditions. While in purely data-driven approaches, all operating conditions need to be represented in the training data, combining these approaches with models and physical reasoning reduces the required amount of training data. Thus, grey-box approaches are ideal if faulty data is rare and expensive to produce. Furthermore, results of grey-box methods typically are easier to interpret than purely data-driven results.



4
EV's concept overview using GPR and traditional models.

Figure 4 shows the early fault detection algorithm's structure. The input data are current, temperature, and SOC, while the battery voltage is considered the reference voltage. Any suspicious behavior in the battery voltage is detected by the machine learning algorithm. The algorithm works in a few steps. First, in a model-based step, a parameterized model, based on the inputs, computes the voltage. Then, in a machine learning step, the modeled voltage, in addition to other inputs, is used in a Gaussian Process Regression (GPR) to predict the uncertainty in the voltage estimation. This uncertainty defines the fault boundary B_f. The modeled voltage is compared to the measured voltage to evaluate whether the voltage deviation R_v lies within B_f. To minimize false alarms, a minimum robust time window t_R during which the fault must be repeated, is defined.

The soft short-circuit error detection result with GPR is shown in Figure 5. As the fault grows, R_v increases towards B_f. A robust window of five seconds ensures that fault alarms that may result from outliers are avoided. As a result, faults are only reported when R_v stays outside B_f for more than t_R = five seconds.

The algorithm takes the measured current, temperature, SoC, and voltage as inputs. The evaluation demonstrates the potential for detecting short circuit anomalies using dynamic GPR thresholds. Utilizing dynamic thresholds determined by GPR, we can categorize and confirm faults, ranging from low to high intensities.

Choosing the right tool for the right risk

Both the VAE-based data-driven method and the grey-box GPR approach provide strong capabilities for early fault detection, but they differ in their requirements, strengths, and ideal use cases. Table 1 summarizes the corresponding strengths of both approaches.

Data-driven methods, such as VAEs, typically require large training datasets, often well above a thousand feature points, to accurately learn hidden patterns and nonlinear relationships within battery signals. Their ability to detect subtle, multidimensional anomalies makes them highly effective for complex systems and varied operating conditions. However, adapting these models to new battery types or system configurations usually requires retraining with fresh datasets. While VAEs excel at identifying intricate data structures, their internal decision processes remain difficult to interpret, which can be a limitation for safety-critical applications.

In contrast, the grey-box GPR approach achieves comparable accuracy with significantly less training data, often just a few dozen representative feature points. By combining a physical battery model with machine-learning-based uncertainty estimation, GPR predicts the expected healthy voltage range and flags deviations in a highly transparent way. This allows the method to generalize better to new operating conditions, making it especially valuable when faulty data is rare or expensive to generate. Its high interpretability also supports safety-relevant decision-making, where understanding why an alarm is triggered is as important as detecting the anomaly itself (for example for traceability and ISO 26262 compliance).

Together, these differences illustrate that VAEs are best suited for pattern-rich environments with ample data. GPRs are particularly suitable in situations demanding low data requirements, physical consistency, and robust real-world applicability.

Property	VAE (data-driven)	GPR (hybrid)
Number of training data	High (>1,000 feature points)	Medium (>50 feature points)
Purpose	Hidden patterns, non-linear correlations	Predict healthy signal range
Accuracy	High, depending on use-case	High, depending on use-case
Scalability to system changes	By retraining with new training data	By model adaptations
Interpretability	Low	High

Table 1
Summary of algorithm properties.

BY
Dr. Maximilian Kloock
kloock@fev.com
Lennart Bauer
bauer_l@fev.com

Conclusion

As battery systems grow in complexity and performance demands increase, active safety measures, such as early fault detection, becomes a decisive factor for ensuring safety, reliability, and long-term value in modern electric vehicles. FEV's digital battery twin demonstrates how the combination of physics-based modeling and advanced AI algorithms can move diagnostics from reactive fault identification to proactive protection and predictive maintenance.

Whether through powerful data-driven methods such as VAEs or through hybrid grey-box approaches like GPR, the ability to detect subtle deviations at an early stage enables targeted interventions, reduces operational risks, and extends the battery lifespan.

By merging interpretable models with scalable analytics, fleet operators and OEMs gain a robust, future-ready framework that adapts to new chemistries, diverse operating conditions, and evolving safety requirements. With these technologies, FEV supports the shift toward safer, more efficient, and more resilient electromobility – supporting the trend for increasing energy densities at lower costs by optimizing safety margins while maintaining high operational safety.

> »A true one-stop-shop solution for comprehensive battery system qualification – from early development to full homologation.«

FEV's eDLP laboratory in Sandersdorf-Brehna, Germany.

#4

FEV eDLP – Certified testing for performance, safety, and compliance

Battery systems have become mission-critical components in modern mobility and energy applications. Whether powering electric vehicles, maritime and aviation propulsion systems, or stationary devices – each application imposes highly specific requirements on the battery system. These are driven by environmental conditions, operational loads, and stringent safety expectations.

Ensuring compliance without slowing down development cycles has therefore become a central challenge for manufacturers. This is where FEV eDLP comes in.

At its accredited battery test laboratory in Sandersdorf-Brehna, Germany, FEV's eDLP combines performance, safety, and transport testing with engineering support and post-test analysis – all under one roof. This integrated approach reduces interfaces, shortens feedback loops, and enables efficient development from early design stages through homologation.

Navigating complex battery regulations

Batteries must not only comply with their operational loads but also withstand environmental conditions and accidental misuse or abuse, as well as global transport from production to installation in order to make for a safe battery system.

These safety-relevant challenges are addressed by international industry standards, as represented in Table 1.

Scope	
Performance	ISO 12405
Safety: Operation and abuse	ECE R100, GB 38031
Safety: Transport	UN 38.3

Table 1
Exemplary industry test standards.

One partner
One facility
One team

These standards translate safety objectives – such as robustness under out-of-spec conditions – into clearly defined test procedures with measurable pass criteria. Exemplary for environmental and misuse conditions, the range of safety-related tests within ECE R100 Rev. 3 and UN 38.3 with module or pack scope are listed in Table 2, along with the associated nomenclature.

While most tests are designed to emulate special transport or operational conditions, ECE R100 even accounts for rare scenarios, such as resistance against burning fuel from another vehicle during an accident, as validated by 9E.

While these standards clearly define what must be tested, they say little about how those tests are to be reliably conducted. For safety-critical components such as battery systems, the credibility of the test results is just as important as the test itself. This is why accreditation according to DIN EN ISO/IEC 17025 therefore becomes essential. It ensures validated processes, calibrated equipment, and globally accepted and harmonized results. At FEV eDLP, ISO 17025 accreditation is not a mere add-on – it forms the operational backbone of all certified testing activities.

Classification		ECE R100 Rev. 3	UN 38.3
Mechanical	Vibration	9A	T.3
	Shock	9C	T.4
	Crush	9D	T.6
Environmental	Thermal shock	9B	T.2
	Fire resistance	9E	
	Altitude		T.1
	Water effects	7B	
Electrical	External short circuit	9F	T.5
	Overcharge	9G	T.7
	Overdischarge	9H	
	Overload (current)	9J	
	Overload (thermal)	9I	

Table 2
Overview of test specifications.

Advanced battery test laboratory

FEV's eDLP provides its customers with comprehensive battery testing infrastructure covering nearly all development and homologation scenarios. Since its launch in 2020, it has been continuously improved to streamline workflows and meet the latest requirements of both regulators and partners.

In addition to electrical performance tests under controlled climatic conditions, the laboratory offers specialized test benches for environmental stress testing. These systems replicate operational and environmental loads, as well as potential misuse scenarios across global climate conditions. Water resistance testing to ensure IPX-compliance is conducted through immersion, cold flushes, and high-pressure water jets. Engineers use salt spray, dust, and rock-chip testing to assess battery housing rigidity. The eDLP is even equipped with a pressurized thermal chamber that allows for emulation of vacuum and ambient pressure variations, such as the type encountered in airfreight scenarios. Finally, an extraordinary 350 kN shaker with its own thermal chamber and power system replicates the expected lifetime vibrations within a compressed timeframe, accelerating development timelines.

For tests beyond the safe operating range, the facility provides four reinforced test chambers, or "bunkers" for abuse testing housed in a dedicated fire hall with exhaust extraction and gas scrubbers. This setup ensures safe and reliable testing without any adverse effects on the surrounding environment.

The ISO 17025 accreditation of eDLP for the aforementioned ISO 12405, ECE R100, and UN 38.3 standards confirms that, in addition to meeting the technical requirements for conducting these tests, the laboratory operates with all the processes necessary to deliver valid, independent and internationally recognized results. Since few facilities currently hold accreditation for this full set of core battery standards globally, the eDLP is well suited to support development programs from prototype to certification testing at one location. With the continued referencing of ISO 17025 in legislation and regulatory frameworks, FEV eDLP provides the expertise and quality assurance needed to meet the legal and procedural requirements of modern battery development.

Engineering beyond testing

The certification tests described earlier are designed to expose battery systems to the maximum stresses expected over their lifetime. Therefore, preliminary development tests may occasionally lead to failures that highlight weaknesses in the existing design. Due to the extreme mechanical load applied to all components, vibration tests on the 350 kN shaker have historically been particularly effective in revealing structural or mounting-related shortcomings of the device under test (DUT).

As an engineering partner, eDLP aims to maximize the information gained from each individual test campaign by adapting additional instrumentation or adapting test parameters – for example, to correlate results with simulation studies. In this sense, vibration tests with up to one hundred synchronized high-frequency sensors have been conducted to obtain spatially resolved representations of the system response.

In addition to comprehensive instrumentation, optimizing the vibration coupling itself is essential to avoid introducing undesired resonances from the test rig into the DUT. This requires careful mechanical design of the mounting interface between DUT and shaker.

In a recent development project for a European OEM, simulation-based pre-assessment of the test setup revealed negative resonance amplifications that would have led to test failure unrelated to the DUT. Based on these results, the customized jig shown in Figure 2 (p. 34) was designed and validated successfully.

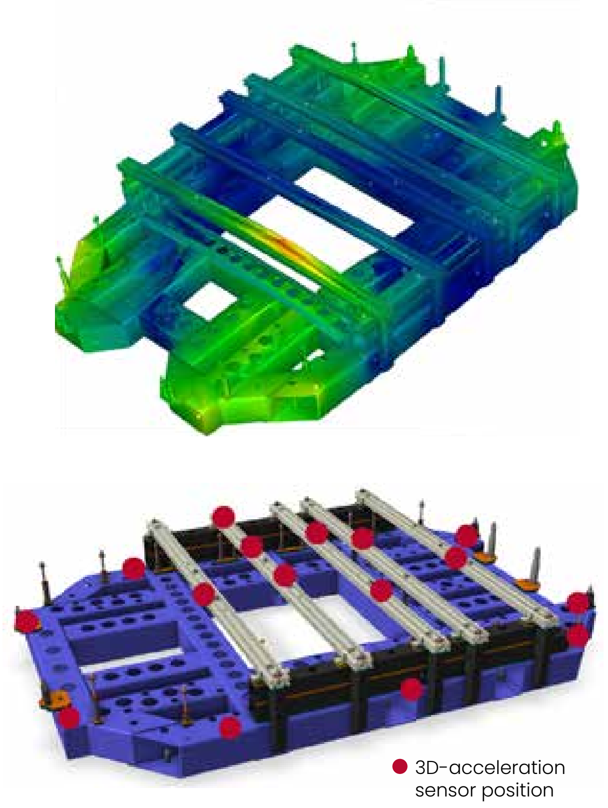
This hybrid approach avoided time-consuming design iterations and cost-intensive test runs for non-DUT-related challenges. This prevented measurement interference, reduced re-testing effort, and significantly accelerated the design validation phase.

1
Insights from eDLP test stands. **1.** Climatic chamber with energy system /
2. IPX-waterjet / **3.** 350-kN shaker with temperature chamber and energy system.

As data volumes increase, identifying relevant metrics and translating them into clear design actions become increasingly challenging. Here, eDLP provides in-depth analytical support through experienced specialists, and – where required – can draw on the broader expertise within the FEV Group. Mechanical simulations, for instance, as shown in Figure 2, allow customers to quickly turn complex data into a clear development path. The same applies even to companies with limited prior experience in battery system testing.

Beyond pass/fail – post-test evaluation analysis for deeper insights

Beyond testing, experienced high-voltage and battery specialists at FEV eDLP perform complete disassembly and expert assessment of battery systems following endurance, environmental and abuse test campaigns. These experts examine even partially damaged battery systems for structural integrity, internal damage progression, electrolyte leakage, weld and busbar conditions, and water ingress. Technical methods such as 3D scanning and CT imaging support this work by detecting subtle mechanical changes and enabling insight into internal structures. As these procedures are nondestructive, they can be applied periodically during long-term test programs. This enables continuous monitoring of critical component behavior over time.



2
Shaker-rig study.
Top: Simulated stress from sinusoidal excitation.
Below: Experimental validation with extensive sensor coverage.

Moreover, this approach delivers insights that go far beyond simple pass/fail criteria of certification tests and offers real development value. The combination of experienced accredited testing and professional post-test analysis ensures that critical failure modes are understood, documented, and fed back directly into the development loop.

Accelerating testing with maximum reliability

Employing a 24/7 shift schedule along with highly automated test execution, the eDLP minimizes downtime and ensures stringent test sequences and continuous supervision. Customizable data handling pipelines prepare and deliver the test results continuously directly into the customer's database for fast feedback into the development loop.

In conjunction with established management systems, these automated processes reduce the risk of human errors. Drawing on many years of experience testing for industry customers, eDLP processes are well-aligned to industry structures.

By consolidating performance, safety, and transport testing at a single location, the eDLP minimizes logistical effort and eliminates unnecessary handovers typically required when development is carried out in a piecemeal manner. This ensures faster, more streamlined communication, as well as more efficient and arguably more effective, test execution.

In a market where safety, compliance, and time-to-market define competitiveness, integrated and accredited battery testing becomes a strategic advantage – not just a technical requirement.

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

The powerhouse for future mobility, software, and energy solutions

fev.com

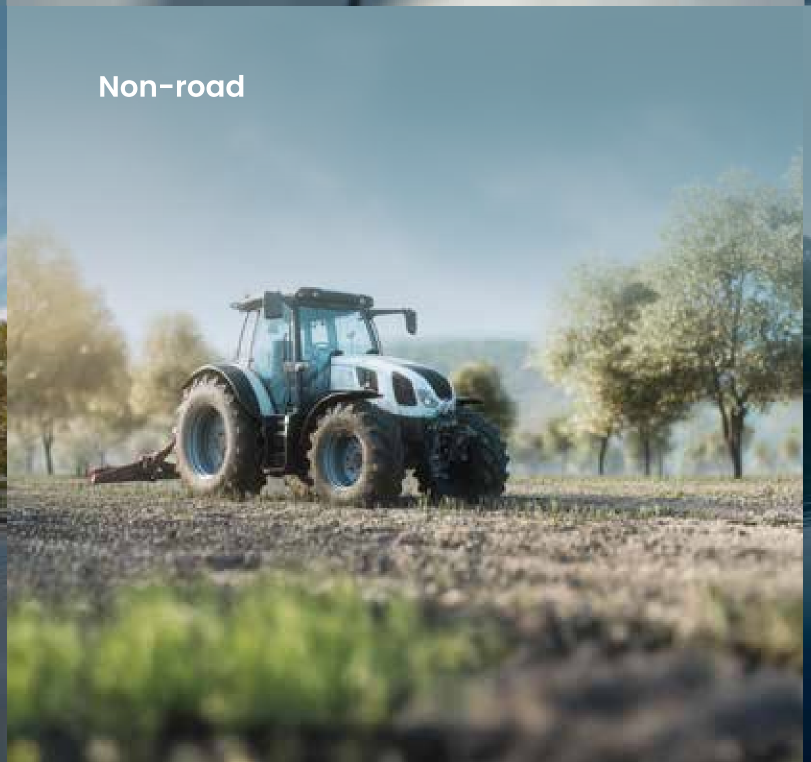

Automotive

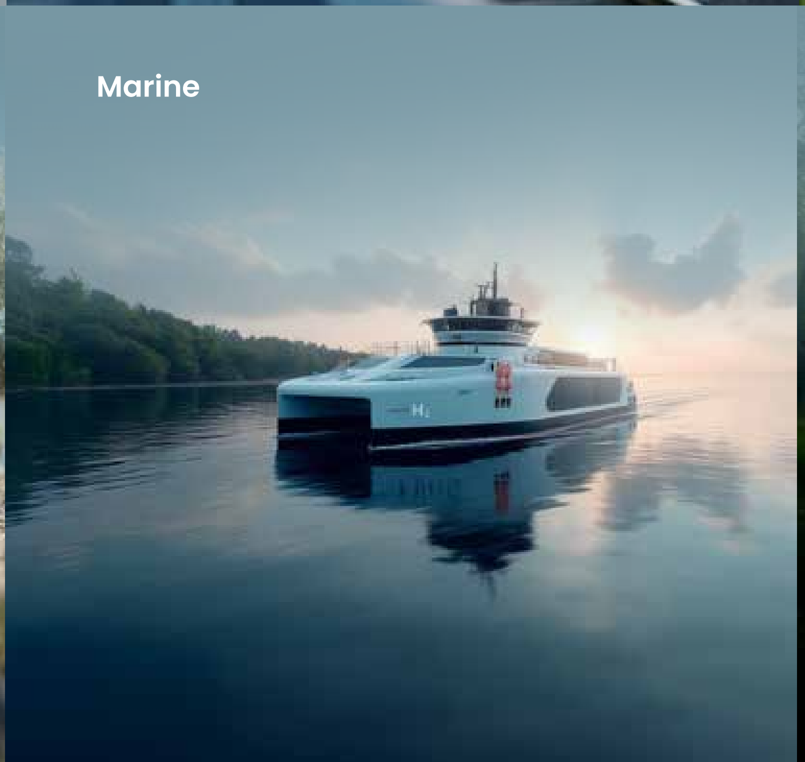

Aerospace


Rail


Energy + resources


Commercial vehicles


Non-road


Marine


Defense

#5

Fuel cell metro trains – A pragmatic pathway to zero-emission urban rail

Emerging cities face increasing pressure to decarbonize urban transport while expanding affordable mass mobility. Although electrified metro systems are well established in major metropolitan areas, their rollout in smaller and mid-sized cities is often constrained by the high cost of trackside electrification infrastructure. Fuel cell electric metro trains (FCEMTs) provide an alternative, combining with high operational flexibility and reduced infrastructure investment.

This article presents an engineering-driven assessment of a fuel cell electric metro train concept tailored to Indian operating conditions. Based on real-world duty cycles and representative passenger loads, the study evaluates powertrain sizing, system weight, cost implications, and packaging feasibility. The results highlight how fuel cell hybrid architectures can enable practical, near-term decarbonization of urban rail – especially where full electrification is not economically viable.

Why fuel cell metro trains matter for India

India has committed to a 45% reduction in CO_2 emissions by 2030, and the transport sector plays a critical role in achieving this target. While battery-electric mobility is growing rapidly in road transport, rail applications present a different challenge. Overhead electrification entails high upfront costs and long implementation timelines, which can be prohibitive for smaller cities.

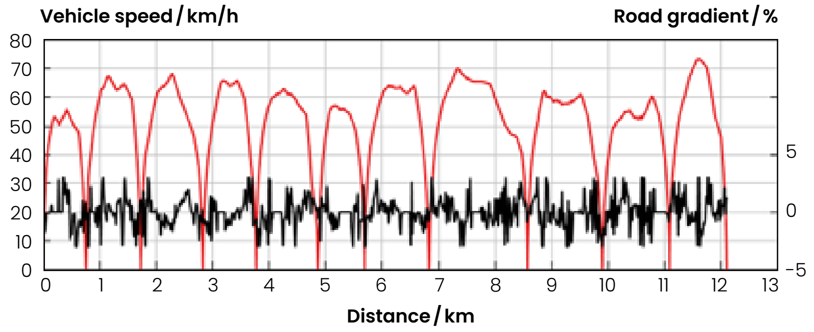
Fuel cell electric metro trains operate independently of overhead lines. Onboard hydrogen is converted into electricity, with a compact high-voltage battery supporting peak power demand and regenerative braking. This hybrid approach combines the range and fast refueling of hydrogen systems with the efficiency benefits of battery buffering – making it particularly attractive for daily, high-utilization metro services.

> »Fuel cell systems can meet demanding metro duty cycles while keeping weight, cost, and packaging within practical limits.«

Reference train and real-world operating conditions

The study is based on a representative three-car metro train used in a tier-1 Indian city. The vehicle has a gross weight of approximately 120 t, a maximum operating speed of 85 km/h, and a motorization rate of ~67%. To reflect real operation, a measured metro drive cycle was used, capturing frequent start-stop events, moderate gradients, and substantial braking energy recuperation.

Daily operation was defined by a target driving range of around 400–450 km, covering multiple service cycles at high passenger occupancy. Extreme crowding conditions, as specified by Indian railway standards, were included to ensure robust powertrain sizing under worst-case scenarios.



1
Real metro drive cycle (velocity and gradient profile).

Hybrid powertrain architecture for efficient metro operation

The fuel cell electric metro train uses a series-hybrid architecture. Hydrogen stored in high-pressure tanks feeds a polymer electrolyte membrane (PEM) fuel cell system, which supplies the typical traction power. A high-voltage lithium-ion battery supports transient loads, captures recuperated braking energy, and stabilizes system operation.

This division of tasks allows the fuel cell to operate predominantly in its high-efficiency range, while the battery handles short-term power peaks. From an engineering perspective, this improves overall efficiency, reduces fuel cell degradation, and reduces required battery size relative to a purely battery-electric train with equivalent range.

System simulation defines optimal powertrain sizing

A validated system simulation environment was used to assess various combinations of fuel cell power and battery capacity.

The key sizing criteria were:

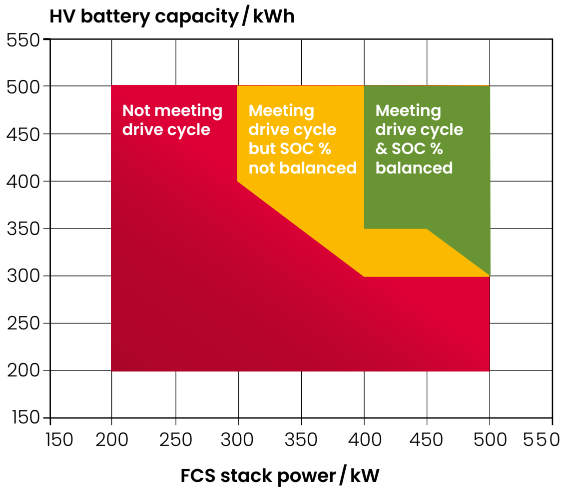
- Meeting peak traction power demand
- Maintaining battery state-of-charge balance over the duty cycle
- Maximizing fuel cell efficiency
- Minimizing system cost and mass
- Ensuring feasible packaging within the vehicle envelope

The analysis identified three viable configurations. Among them, a combination of a 400 kW fuel cell system and a 350 kWh high-voltage battery emerged as the best overall compromise. This setup meets performance requirements, maintains battery charge balance, and offers the lowest combined system weight and cost.

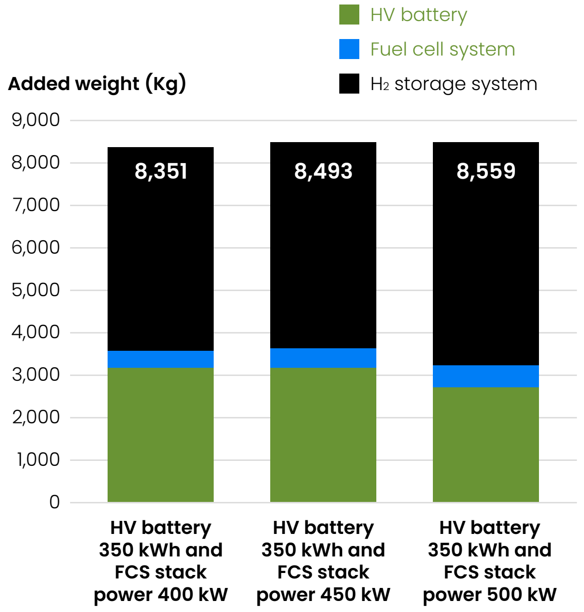
Hydrogen consumption, system weight, and cost implications

For a full day of operation covering approximately 440 km, the selected configuration requires around 215 kg of hydrogen, corresponding to an average consumption of about 49 kg per 100 km under demanding operating conditions. This consumption level is well within the capabilities of current 350-bar compressed hydrogen storage systems specified for Indian rail applications.

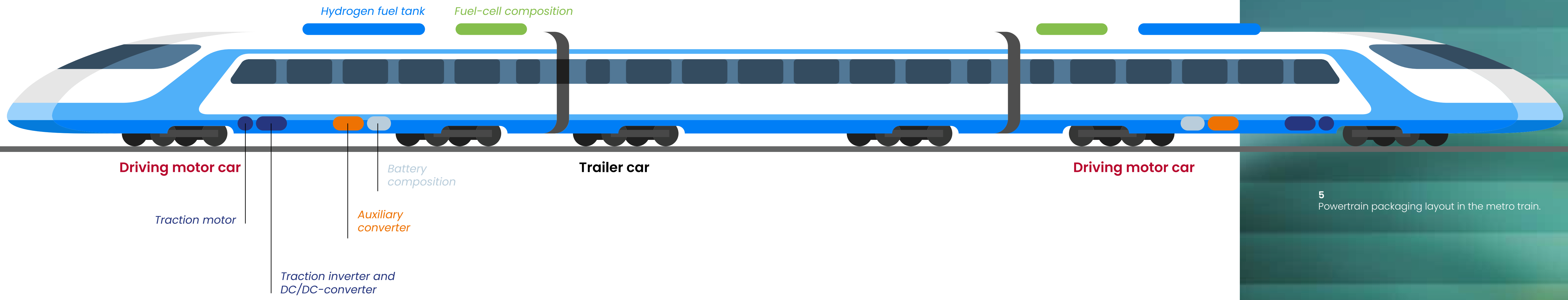
From a weight perspective, the complete energy system – fuel cell, battery, and hydrogen storage – adds roughly 8.3 t to the vehicle. This is significantly lower than a long-range battery-only solution and remains compatible with axle load limits.



2
Fuel cell battery sizing map.



3
System weight breakdown of selected configurations.



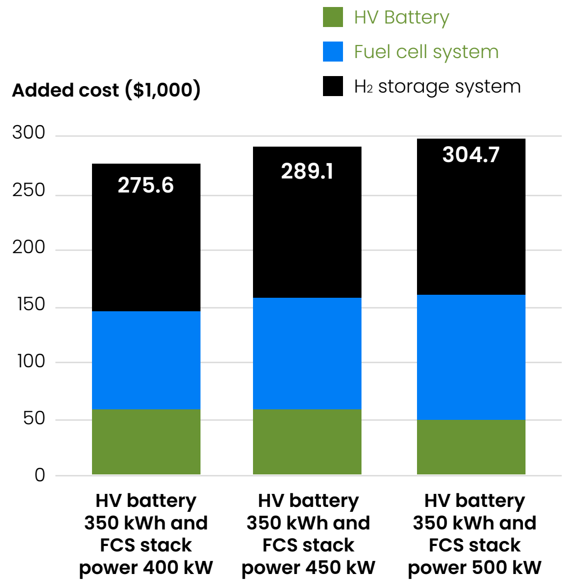
5
Powertrain packaging layout in the metro train.

Cost analysis shows that hydrogen storage and the fuel cell system dominate the powertrain cost, while a reduced battery size helps limit overall investment. At current hydrogen prices in India, the estimated operating cost is competitive with diesel-based rail solutions and expected to improve further as green hydrogen production scales up.

Integrating fuel cell systems into metro vehicles

A critical question for any alternative powertrain is whether it can be integrated into existing vehicle platforms. The study demonstrates that this is feasible for metro trains of the selected size. Hydrogen tanks and fuel cell modules can be mounted on the roof, while batteries and power electronics are placed underfloor in the driving motor cars.

The available roof and underfloor areas are sufficient to accommodate all major components without compromising passenger space or vehicle dynamics. This enables both new vehicle designs and potential retrofit concepts for existing rolling stock platforms.



4
System cost comparison of powertrain configurations.

Hydrogen infrastructure as a scalable alternative

The success of fuel cell metro trains depends not only on vehicle technology but also on energy infrastructure. Today, hydrogen refueling infrastructure remains limited in India. However, national initiatives to scale up green hydrogen production and reduce costs are already underway.

Compared to continuous overhead electrification, localized hydrogen refueling at depots offers a more modular and scalable infrastructure model. This is particularly attractive for smaller metro networks with shorter routes and centralized operations.

BY
Ashraf Emran
emran@fev.com
Marius Walters
walters_m@fev.com
Shivam Garg
garg@fev.com
Matthias Thewes
thewes@fev.com

Conclusion

Fuel cell electric metro trains represent a technically robust and economically attractive option for zero-emission urban rail in India. The presented concept demonstrates that, through realistic component sizing and hybridization, fuel cell systems can meet demanding metro duty cycles while maintaining weight, cost, and packaging within practical limits.

As hydrogen availability improves and costs decline, FCEMTs can complement conventional electrified metros – especially in cities where infrastructure investment must be carefully balanced against environmental targets. From an engineering and system-integration perspective, fuel cell metro trains are no longer a distant vision but a viable solution ready for real-world deployment.

#6

From diesel to ammonia – CO_2-reduced commercial propulsion

The decarbonization of commercial propulsion systems is accelerating under increasing regulatory pressure and tightening greenhouse gas targets in the maritime sector globally. While electrification and hydrogen are discussed as long-term solutions, ammonia is emerging as a promising carbon-free energy carrier alternative to diesel in the near-term, due to its comparatively simple storage and established global handling infrastructure. Especially for ship propulsion, including in naval applications, ammonia offers the potential to significantly reduce CO_2 emissions without fundamentally redesigning existing engine platforms.*

FEV has therefore performed an experimental study on a modern 2.13 L single-cylinder research engine derived from a diesel platform to investigate the emerging technology trends for ammonia combustion. This study was complemented by three-dimensional CFD modeling, enabling an accurate reproduction of the in-cylinder processes to facilitate detailed investigation of the influence the diesel pilot quantity exerts over the start of combustion and flame propagation, with a focus on efficiency and emissions improvements.

For OEMs, this approach provides a pragmatic entry into ammonia-based propulsion. By leveraging proven diesel engine platforms, development efforts can focus on targeted combustion and fuel system adaptations rather than complete platform redesigns. This significantly shortens development cycles, reduces capital expenditure, and enables manufacturers to meet regulatory requirements while maintaining technological continuity.

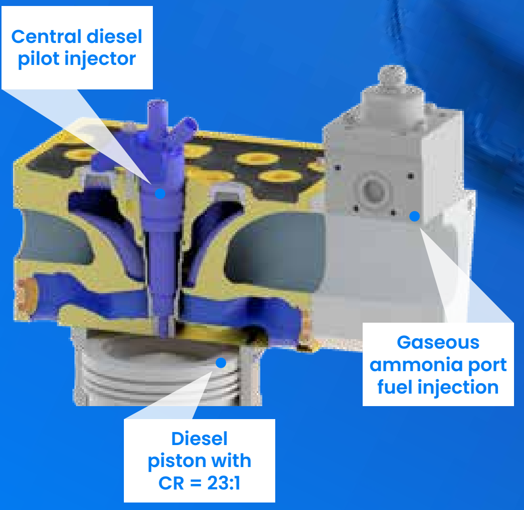
Set-up of a high-speed single cylinder engine

The main characteristics of the 2.13 L single cylinder research engine derived from a diesel platform are shown in Table 1.

* For more on ammonia fuel and combustion properties, check Spectrum #80, from page 48: ***Fueling the future – Unlocking ammonia's potential in high-speed marine applications***

Description	Unit	Value
Bore/stroke	mm	132/156
Displacement	cm^3	2,135
Compression ratio	-	23:1
Peak pressure capability	bar	300
Coolant/oil temperature	°C	90/90
Fuel pressure diesel	bar	600 – 2,000
Fuel pressure ammonia	bar	p_{intake} + 0.5 to 3.0 (depending on load point)

Table 1
Specifications, set-up and boundary conditions of the single-cylinder combustion engine.



To enable dual-fuel operation with a load-dependent mixture of diesel and ammonia, the original piston was exchanged for a new variant and an ammonia (port fuel injection) injector was mounted at the entry of the intake port. The new piston featured an altered bowl geometry with reduced volume to achieve a compression ratio of 23:1, while maintaining the original bowl contour. This was done for two purposes. First, to secure the ignition of the pilot diesel injection quantity under all load conditions, and second, to support proper combustion behavior of the ammonia quantity used as the main energy source.

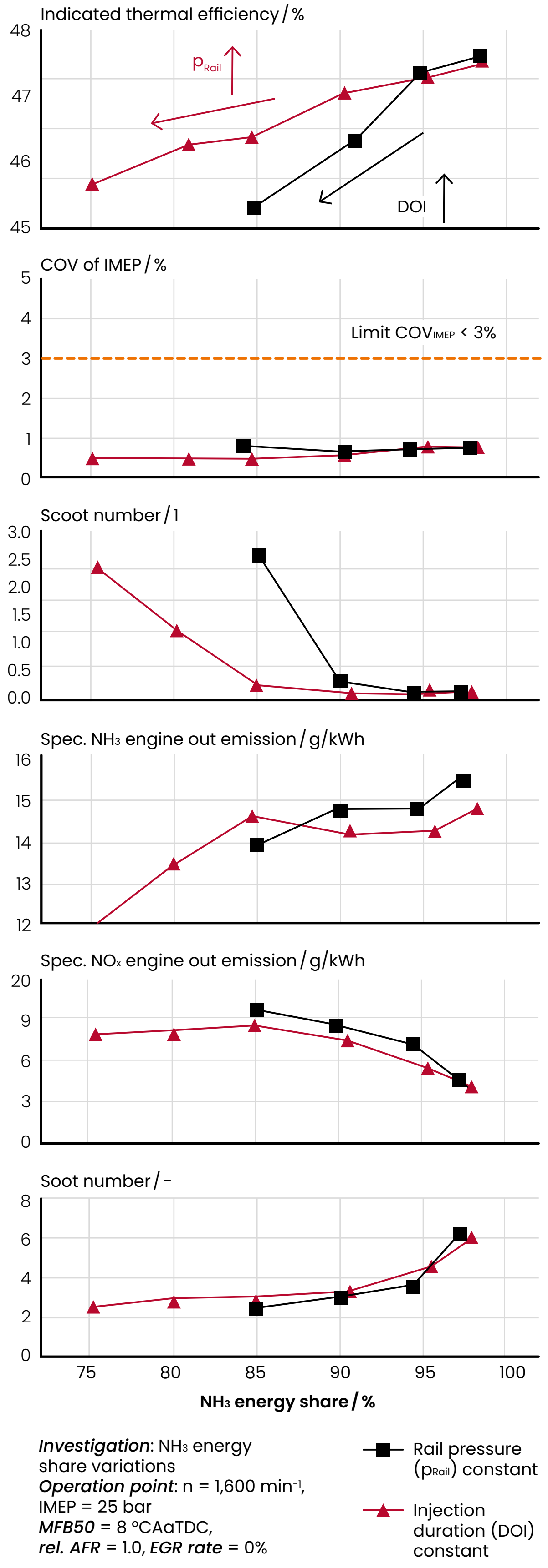
Ammonia/diesel dual-fuel pilot ignition optimization

To characterize the most favorable starting point for the optimization and tuning campaign, the diesel pilot injection was optimized at the rated-power point, as shown in Figure 1.

The pilot rail pressure and pilot injection duration varied independently, starting from a common reference setting defined by the minimum achievable rail pressure and injection duration. This setting enabled maximum ammonia substitution, reaching an ammonia energy share of 98%. Under these conditions, an indicated efficiency of 47.5% was obtained while achieving an excellent combustion stability with a coefficient of variation (COV) of IMEP <1%. Thanks to increasing diesel energy share, the indicated thermal efficiency decreased in both cases, mainly due to incomplete oxidation of the additional diesel, leading to a pronounced increase in CO and soot. Increasing pilot rail pressure improves spray atomization and enhances the premixed fraction of the pilot, thereby promoting faster early heat release and reducing the efficiency penalty compared with increasing pilot duration.

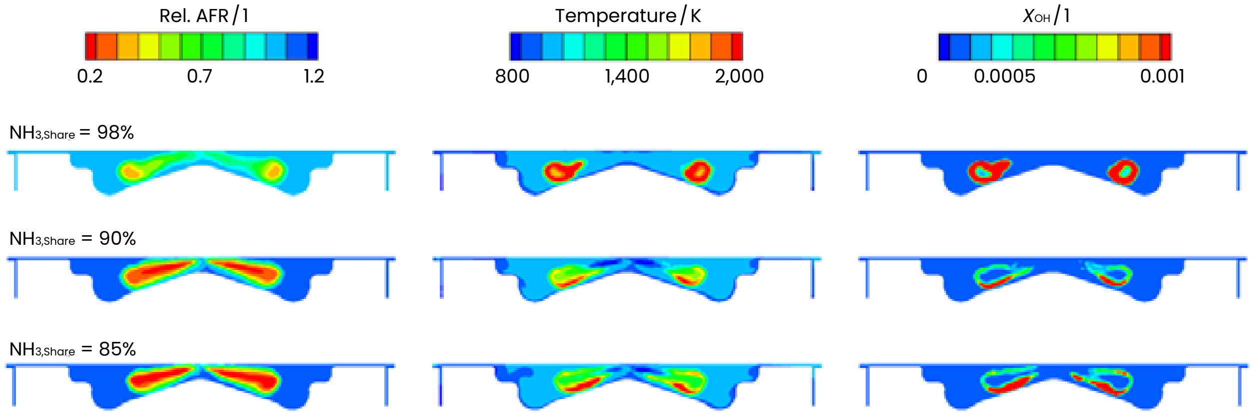
High ammonia substitution ratios are, however, associated with increased unburned ammonia under the premixed combustion concept. Ammonia located near the walls and in crevice volumes remains partially unreacted due to its low laminar flame speed and strong quenching effects. In contrast, NO_x emissions decrease with increasing ammonia energy share because in-cylinder temperatures are reduced and thermal NO_x formation is suppressed. Above 90% ammonia energy share, the emission trends of both pilot strategies are similar, as the diesel fraction is small and can be oxidized more completely.

An ammonia energy share of approximately 95% represents a practical compromise, as it avoids excessive local diesel pilot enrichment while limiting ammonia slip. In this range, elevated pilot rail pressure is preferable because it promotes more complete pilot diesel oxidation and mitigates the tendency for efficiency deterioration. The coupled response of ammonia slip and NO_x to ammonia energy share enables the engine-out NH_3/NO_x ratio to be adjusted to roughly 2–4. However, this remains above the target value of ~1 required for high-efficiency SCR-based $DeNO_x$ operation. Fortunately, the global relative air/fuel ratio (AFR) can be used as an additional control lever to further shift the engine-out NH_3/NO_x ratio toward unity.



Investigation: NH_3 energy share variations
Operation point: n = 1,600 min^{-1}, IMEP = 25 bar
MFB50 = 8 °CAaTDC,
rel. AFR = 1.0, ***EGR rate*** = 0%

1
Diesel pilot injection optimization at rated power conditions.



2
Lambda, temperature, and OH mass fraction distributions at 5° CA bTDC for the different NH_3 energy shares (n = 1,600 min^{-1}, IMEP = 25 bar, CR = 23:1).

3D-CFD simulation (results)

Three-dimensional CFD simulations are performed to investigate the diesel ignition process and the subsequent flame propagation during dual-fuel operation with ammonia and diesel. The initial NH_3 mass fraction differs slightly between cases due to the varying ammonia energy shares investigated. Analysis of species distributions and heat release rate indicates that combustion onset occurs earliest at the lowest diesel share, which results from a slightly earlier injection timing in this configuration. The three-dimensional visualizations at 5° before Top Dead Center (bTDC) (Figure 2) confirm that autoignition remains effective even at minimal diesel quantities, with ignition kernels appearing exclusively at the diesel spray tip. As the injected diesel quantity increases, the fuel undergoes broader spatial distribution, though this extended dispersion provides no measurable advantage for ignition quality.

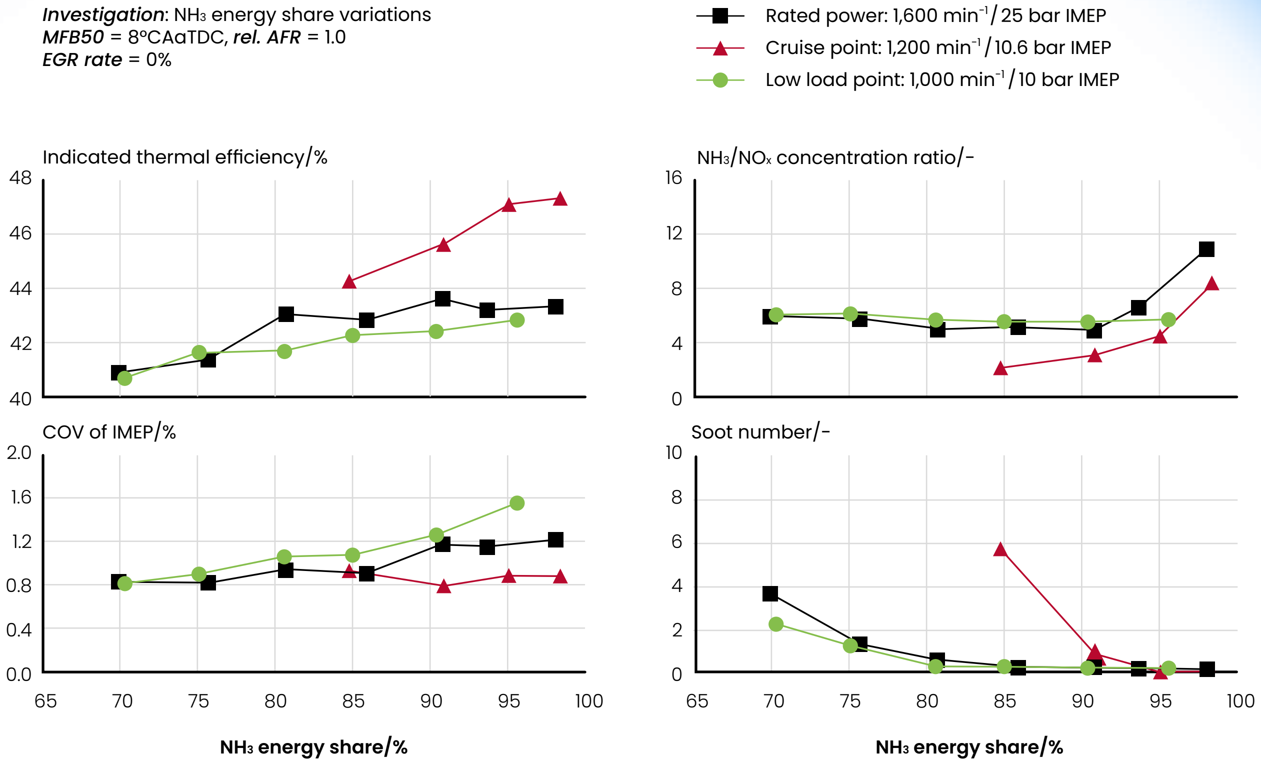
The nearly identical combustion rate can be explained by the transition of the flame from diffusive combustion to conventional flame propagation.

The overall combustion phasing does not change significantly with increasing diesel fractions, since the onset of diffusive diesel combustion simultaneously initiates the progressive NH_3 combustion. At lower diesel fractions, the enhanced formation of OH radicals accelerates the combustion to a similar extent, resulting in a comparable overall combustion behavior. Furthermore, it can be demonstrated that even a very small diesel pilot quantity is sufficient to ignite NH_3 and establish stable, effective flame propagation.

Operation strategy

To determine the potential of ammonia usage across the engine map, three operating points were analyzed in more detail: the rated power point, the cruise point for on-road, heavy-duty applications, and a reduced-speed point at a load comparable to the cruise point. The final point was chosen to illustrate the impact of engine speed on the operation behavior. In these operating points, ammonia energy share variations under stoichiometric conditions were conducted to derive a suitable ammonia/diesel split for the engine map. The results are shown in Figure 3.

Engine efficiency is mainly impacted by the IMEP and ammonia share. As such, it is crucial that the ammonia share is maximized while maintaining stable combustion. Due to the high knock resistance of ammonia, no knock events were observed at rated power even at high pre-mixed shares. At high loads, ammonia slip is reduced, making it easier to achieve an NH_3/NO_x ratio close to unity than at the low-load points. Moreover, combustion stability rapidly decreases with higher ammonia shares, as ignitability becomes more challenging at lower temperatures. This effect is especially pronounced at lower engine speeds. While higher diesel shares are desirable for both

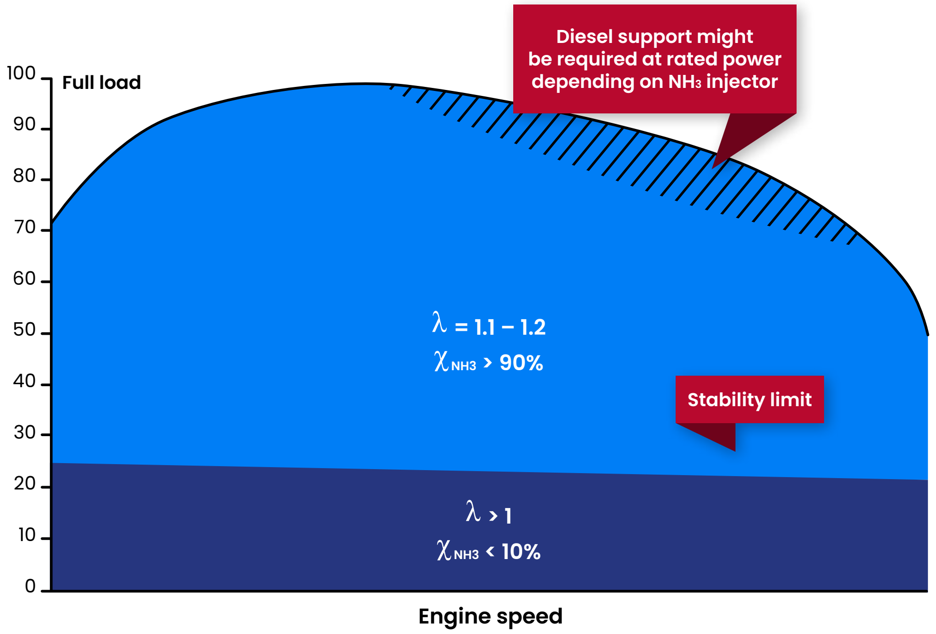


3
Ammonia energy share in different operating points.

combustion efficiency and the exhaust aftertreatment system, soot formation can occur because of low oxygen availability. These results indicate that the acceptable ammonia energy share depends strongly on the demanded engine output.

By further analyzing all test bench results, an operating strategy for the engine map can be derived. The goals for this approach are to maximize the ammonia share across the entire map to achieve the lowest possible greenhouse gas emissions. Ensuring stable engine operation is a secondary objective. Furthermore, keeping the total NO_x and ammonia emissions at a low level while targeting an engine-out NH_3/NO_x ratio close to one enables an effective use of a diesel-based exhaust gas aftertreatment system to decrease both emissions. Figure 4 schematically illustrates the derived operating strategy.

The engine map is divided into two parts: a low part-load section where predominantly diesel is used to achieve stable combustion due to ammonia's high ignition requirement, and a higher load area with ammonia as the main fuel. At part-load, diffusive combustion has the additional benefit of enabling a quality-controlled operating strategy to minimize throttling losses. Small quantities of ammonia can be injected in the higher load area to reduce CO_2 emissions and to generate ammonia slip for the exhaust aftertreatment system. As soon as a stable operation with ammonia can be ensured, a quantity-controlled approach is used to achieve a lean lambda setpoint of $\lambda = 1.1 – 1.2$, which results in a NH_3/NO_x ratio close to unity while keeping unburnt diesel emissions low. Due to ammonia's high resistance to knock, reducing the pre-mixed share of ammonia at full load is not required. However, an optional increase of the diesel share in the rated power area might be required if the ammonia fuel injection system cannot provide enough fuel to achieve the target full load. However, due to soot formation, the amount of support diesel fuel must be kept as small as possible.



4
Diesel/ammonia dual-fuel operation strategy.

Conclusion

FEV has demonstrated on a 2.13-L single-cylinder engine that ammonia is a feasible carbon-free fuel for high-speed marine engines. The ammonia-diesel dual-fuel concept is based on an existing diesel platform. It requires only manageable hardware changes and offers a practical near-term retrofit route with comparatively low cost and limited modifications to current engine architectures. The proposed system demonstrated performance comparable to the diesel baseline in terms of load capability, operational stability, and efficiency while achieving an ammonia substitution level above 98%. Under slightly lean conditions, an indicated efficiency close to 50% was obtained. Although the investigations were conducted on a single-cylinder research engine, the fundamental combustion characteristics and calibration trends are expected to remain valid in multi-cylinder high-speed engines when supported by robust system integration and balanced cylinder-to-cylinder variations.

As expected, the reduction in greenhouse gas emissions is accompanied by increased unburned ammonia in exhaust. Importantly, ammonia slip can serve as a reductant for NO_x in a SCR system, enabling simultaneous mitigation of ammonia slip and NO_x. A key requirement for this approach is maintaining an NH_x/NO_x ratio close to unity at the SCR inlet, which can be achieved through targeted calibration of the ammonia energy share and the relative air/fuel ratio across the operating map. Beyond the demonstrated baseline configuration, ammonia's high knock resistance offers additional margin for efficiency improvements. The main limitation of the current premixed combustion strategy remains elevated ammonia slip. Therefore, future development will focus on combustion-system measures to reduce ammonia slip, including alternative combustion chamber geometries and advanced charge-motion concepts, while preserving stability and high efficiency.

BY
Zhengling Li, TME
li_zhengling@tme.rwth-aachen.de
Arne Güdden
guedden@fev.com
Christian Wouters
wouters_ch@fev.com

Signature Solutions

ONLY AT FEV!

#7
SPECTRUM regularly presents a selection of unique FEV solutions

Further FEV Signature Solutions:
fev.group/solutions

Powertrain concept development for electric and hybrid vehicles

Selecting the right powertrain architecture has become one of the most critical steps in the development of electric and hybrid vehicles. Vehicle range, performance, efficiency, and cost are strongly influenced by decisions made during the early concept phase. This is particularly true for high-performance electric sedans and heavy-duty trucks, where multi-speed electric drive units (EDUs) are increasingly required. In such systems, determining the optimal number of gears as well as the size and number of electric motors becomes a key design challenge.

FEV addresses this task with its Powertrain Designer Tool, a simulation environment developed to support the early design of electrified powertrains. The tool allows engineers to translate vehicle requirements into a technical powertrain concept. Furthermore, it helps to determine suitable component dimensions for electric machines, transmissions, and battery systems.

Based on defined vehicle targets and driving cycles, the tool calculates the power demand at the wheels and derives the corresponding requirements for the drivetrain components. In addition to standard driving cycles, specific performance tests – such as hill-climbing capability – can be simulated to determine the exact load and performance requirements for the propulsion system.

Using backward simulation, engineers can evaluate vehicle performance, energy consumption, and system loads under realistic operating conditions. This makes it possible to analyze a large number of design variants in a short time. Different drivetrain architectures, gear ratios, and component sizes can be compared quantitatively, helping development teams identify suitable system concepts before entering detailed design phases.

AI-based optimization algorithms can be applied to automatically search the design space and identify optimal powertrain configurations for defined vehicle targets.

The Powertrain Designer Tool is integrated into FEV's system engineering workflow and supports key development steps such as system sizing, parameterization, and concept validation. For manufacturers, this enables faster concept studies and provides a solid analytical basis for early architecture decisions.

Fuel cell stack development – From concept to validated performance

As fuel cell propulsion moves closer to series applications, manufacturers face the challenge of developing stacks that meet demanding targets for performance, durability, and packaging.

FEV supports this transition with a structured stack development process that covers the complete engineering chain – from cell design to validated system performance. The approach combines simulation-driven design, component development, system integration, and validation on dedicated test benches.

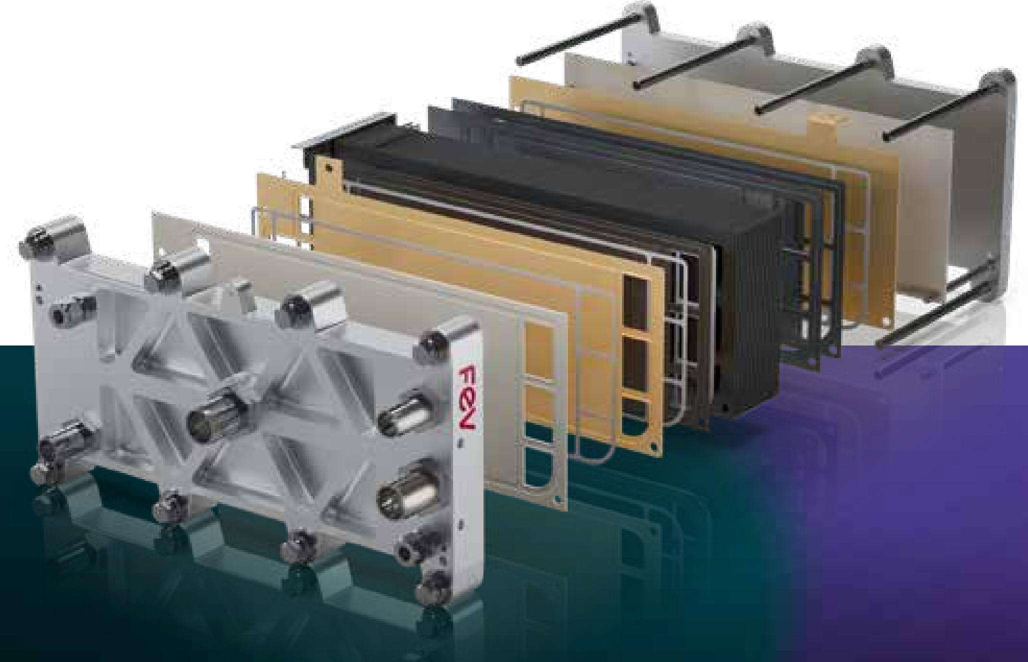
Development begins with the design and optimization of the stack's core components. This includes bipolar plates, membrane electrode assemblies (MEA), compression systems, sealing concepts, and the electric system layout. Simulation methods such as CFD flow-field analysis, structural FE simulations, and system modeling allow engineers to evaluate design variants early and identify robust solutions before prototype hardware is built.

For customers, this front-loaded engineering approach reduces development loops and testing effort. Design decisions can be validated early in the process, helping to avoid costly redesigns later in the program and supporting a predictable development timeline.

Beyond stack development, FEV also supports system integration. This includes the design and build of fuel cell systems, integration of balance-of-plant components, vehicle integration, and preparation for homologation.

Validation is carried out on dedicated fuel cell test benches. Performance testing and accelerated aging tests provide insights into durability and degradation behavior under realistic operating conditions while shortening development timelines.

This combination of simulation, system engineering, and testing provides manufacturers with a clear pathway from early design to validated fuel cell stacks for real-world applications.



5,600 FEV experts 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

SPECTRUM #82
Issue 01/2026

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