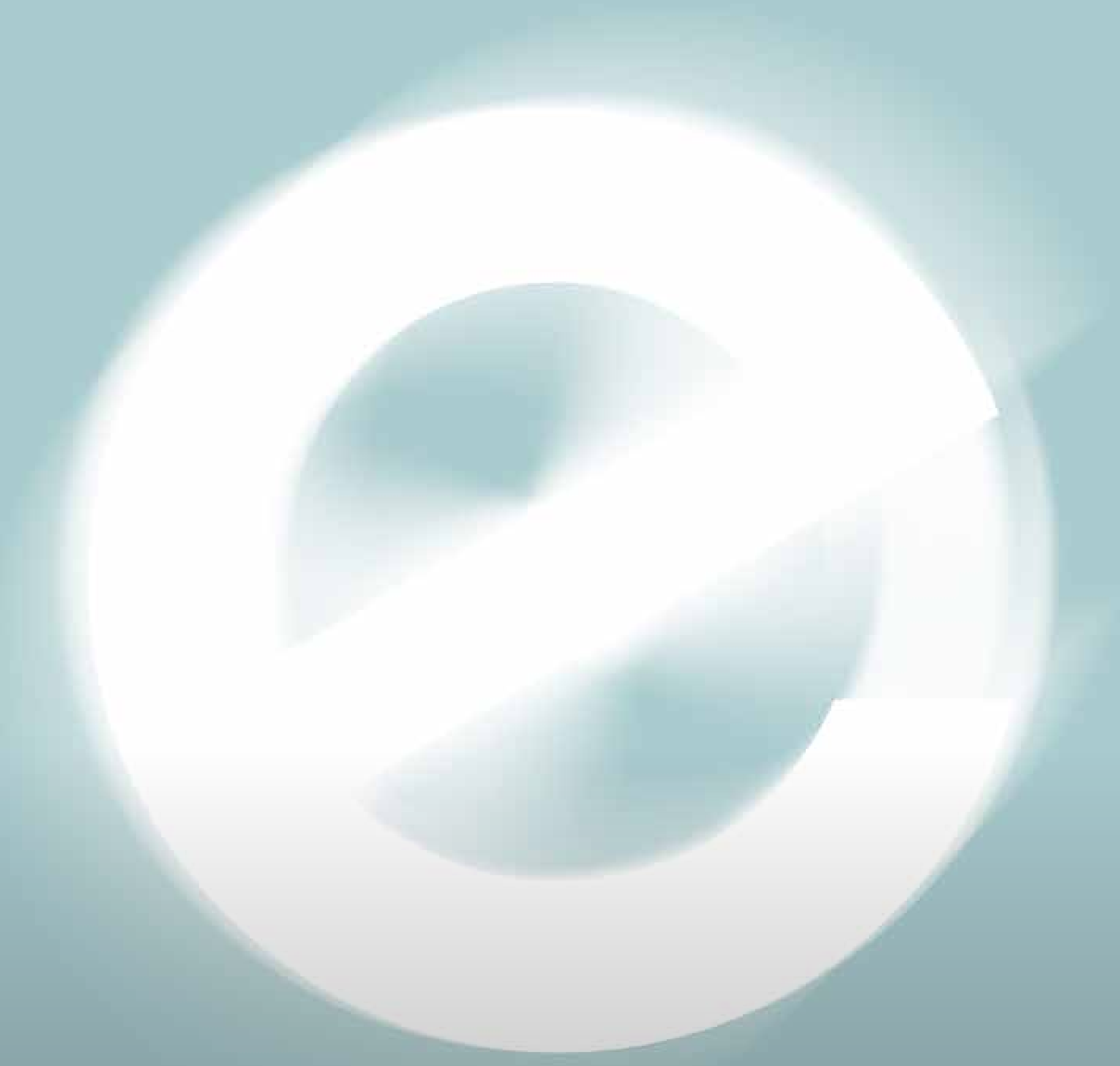
FEV

#80
SPECTRUM



feel evolution

Dear readers,

the landscape of mobility and energy is undergoing a profound transformation. At FEV, we are actively shaping this future, driven by our commitment to innovation, sustainability, and efficiency. In this issue of our customer magazine, we showcase cutting-edge developments that push the boundaries of what is possible across industries.

Artificial intelligence is accelerating engineering processes, and our FEV GenAI Hub is at the forefront of this evolution, enabling ever more cost-efficient and rapid development cycles. Meanwhile, as the demand for battery electric vehicles grows, our latest research demonstrates how sub-10-minute charging times can be achieved through advanced battery technology and optimized thermal management, eliminating a significant barrier to widespread EV adoption.

We continue to lead in sustainable powertrain solutions. Our work on next-generation battery management systems unlocks the full potential of emerging cell chemistries, while our expertise in electric drive units ensures that future powertrains are more efficient, durable, and cost-effective. Similarly, in this issue of SPECTRUM we showcase developments in hybrid battery electric vehicles which are gaining traction as a viable bridge to climate-neutral mobility, combining the best of both ICE and BEV technologies.

Our competencies in the field of energy and resources further strengthen this vision, with innovative solutions for renewable energy systems, energy storage, and holistic sector coupling.

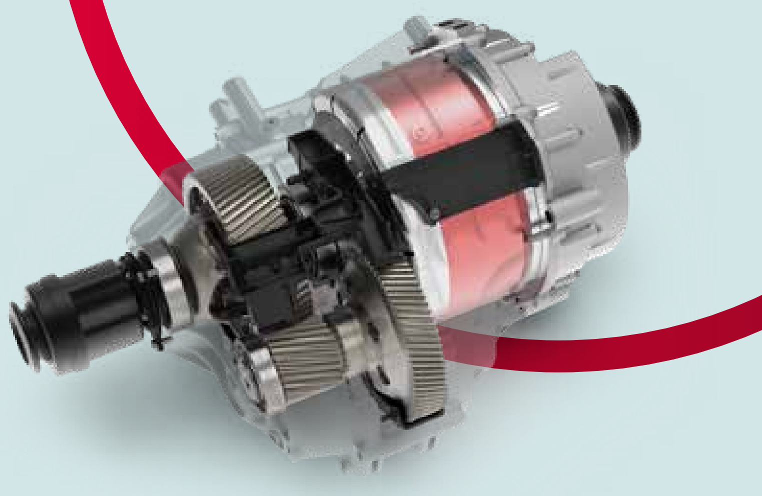
Hydrogen and alternative fuels remain critical pillars in the decarbonization of transportation as well. Breaking the 30-bar barrier in hydrogen-fueled engines marks a milestone for commercial applications. Ammonia's potential for high-speed marine engines is equally promising, paving the way for sustainable propulsion in the maritime sector. In aviation, our work on fuel cells and sustainable aviation fuels underscores FEV's commitment to making air transport more environmentally friendly, with innovative solutions tailored to the industry's unique challenges.

We hope you find inspiration in the pioneering developments featured in this issue – embodied in the rotating "e" of our company name on the cover. Let's continue working together toward a smarter, cleaner, and more efficient future.

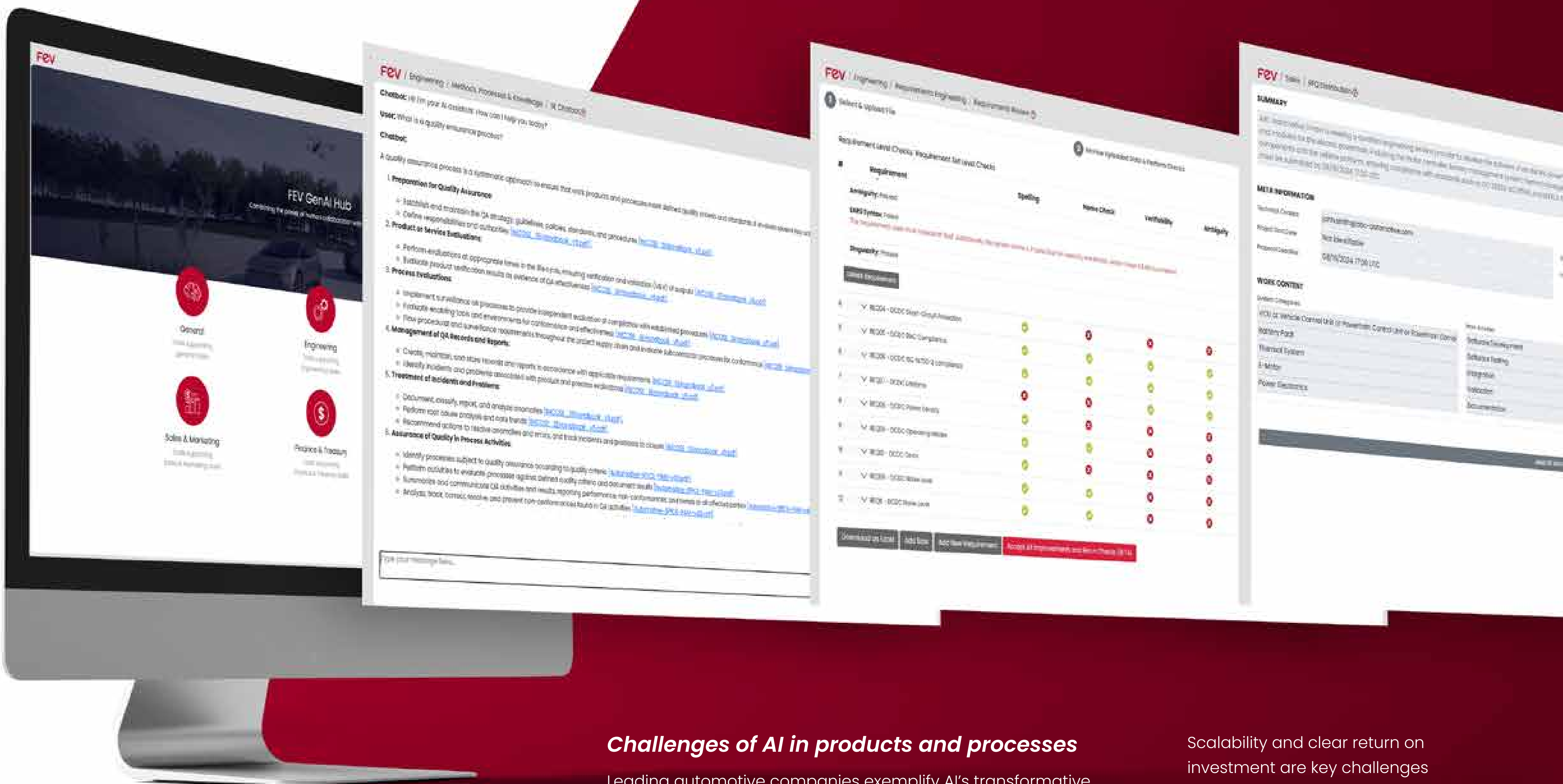
Enjoy the read!

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

CONTENT



#1
FEV GenAI Hub – Cutting complexity, boosting speed



The integration of artificial intelligence (AI) in industrial applications is quickly becoming a cornerstone of modern industry, driving innovation through image processing, voice control, data analytics, predictive maintenance, and digital twins. Its influence extends beyond the final product, revolutionizing engineering processes. To fully harness AI's potential, it is crucial to contextualize AI use cases, enabling the integration of multiple applications into a cohesive interdisciplinary workflow.

GenAI Hub

Challenges of AI in products and processes

Leading automotive companies exemplify AI's transformative power, yet the journey toward a data-driven, AI-powered future is still ongoing. Despite rapid advancements, many companies face challenges in practical AI application, hindered by a fragmented landscape. Effective data management strategies are essential to ensure large-scale storage, availability, and compliance of labeled datasets, maintaining confidentiality and data integrity while providing tailored access for deploying novel AI solutions.

In an era of abundant underutilized data and numerous automation opportunities, effectiveness is paramount. Companies often overemphasize machine learning expertise, neglecting the importance of domain engineering know-how. Multidisciplinary AI teams – comprising machine learning specialists and domain experts – are essential for practical engineering applications. Without strong collaboration, AI models risk becoming academic exercises rather than tools providing real business value.

Scalability and clear return on investment are key challenges in AI adoption. While pilot projects demonstrate significant cost-saving potential, they often remain isolated due to a lack of overarching strategy. The success of AI tools depends heavily on specific training data and processes, limiting their applicability across different contexts. Rigorous validation is essential to mitigate risks and build trust, while rapid deployment and seamless integration with existing systems are crucial for leveraging efficiency gains.

Leveraging systems engineering to enable AI

To address these challenges, FEV developed the systems engineering solution C.U.B.E. (Compositional Unified System-based Engineering). C.U.B.E. structures engineering processes and artifacts using defined engineering views and decomposition levels, ensuring consistent dependencies throughout product development.

FEV's second solution is the GenAI Hub (figure 2), a centrally managed platform built on a secure architecture within the FEV cloud, effectively handling network security and data protection. The GenAI Hub ensures efficient data collection and processing while maintaining compliance. Its modular approach facilitates the reusability of software functions and supports global AI solution deployment. Thus, it enables an efficient user feedback collection essential for a continuous integration and continuous deployment (CI/CD) approach.

Strategic avenues for AI adoption

Once these structures are established, identifying potential AI use cases is the next step. Companies generally adopt AI through two strategic avenues: revenue focus and efficiency focus. The revenue-focused approach involves developing AI-enhanced products and services to create new business opportunities, while the efficiency-focused approach aims to optimize internal engineering processes and enhance productivity.

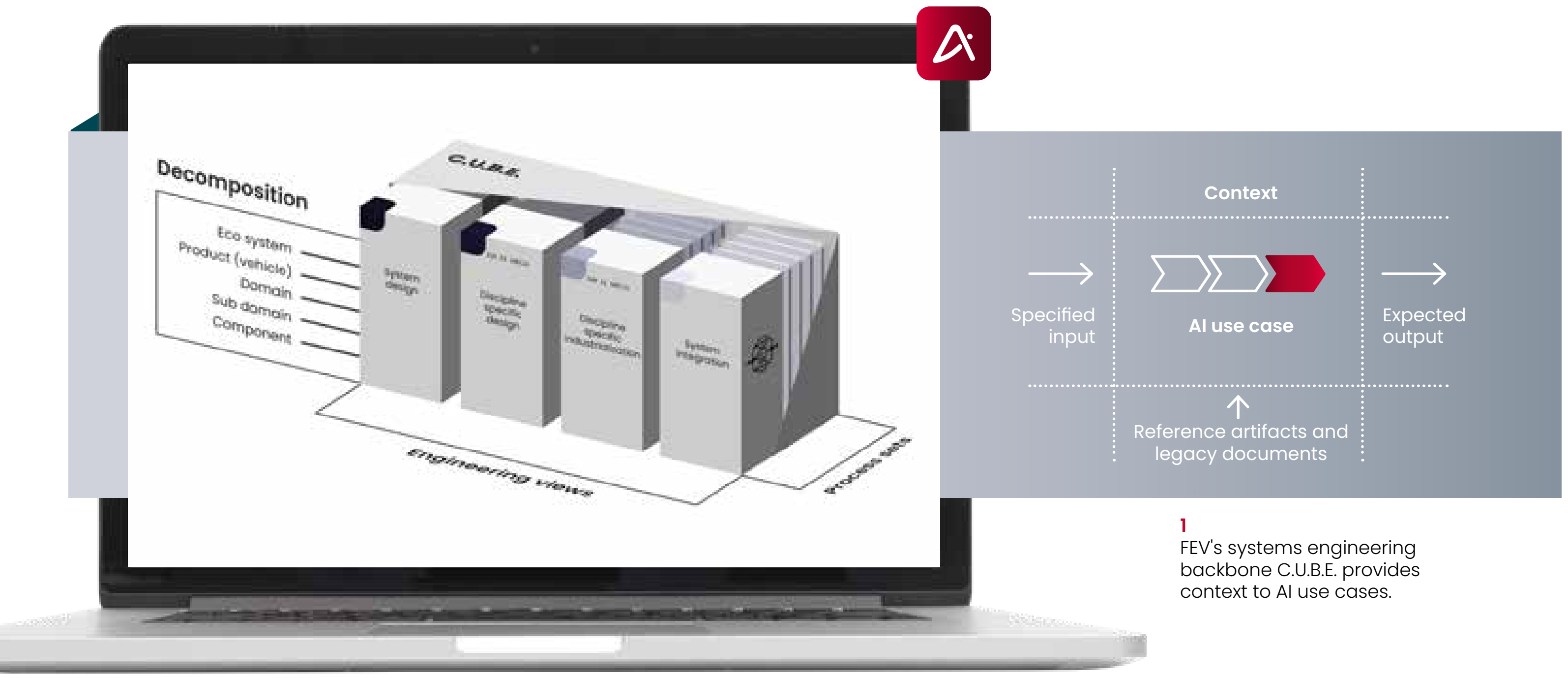
FEV's structured approach to identifying and prioritizing AI use cases starts with generating potential applications, filtering them by readiness and risk, categorizing them, and selecting the most valuable and feasible ones for implementation.

AI-driven requirements engineering

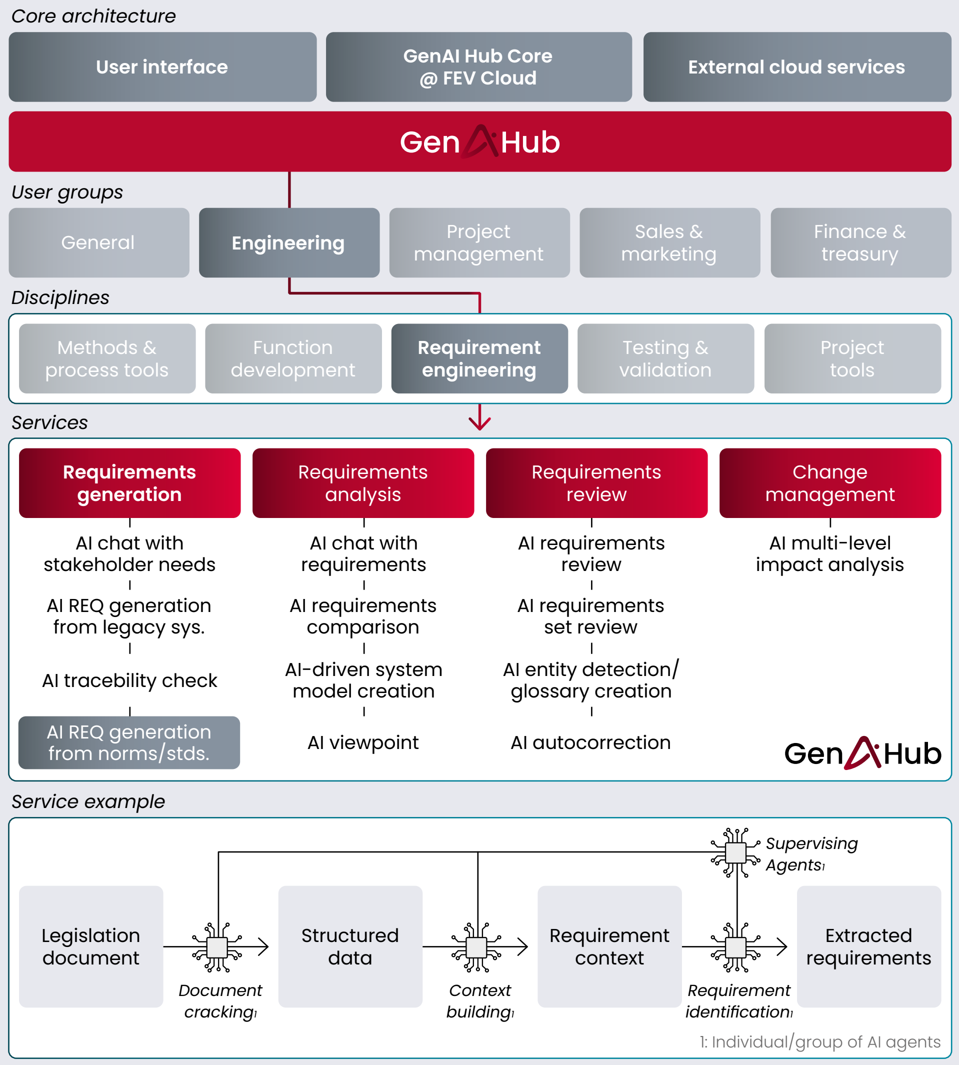
AI's role in automating requirements management is one of its most impactful applications in engineering. Since this discipline is based on natural language, advancements in natural language processing (NLP) offer significant benefits. Applications range from collecting and extracting requirements from regulations to linking and decomposing requirements across system levels, and reviewing them for attributes like testability, ambiguity, consistency, or uniqueness.

The robust extraction of structured, reusable, and processable data from documents is particularly crucial. Modern large language models (LLMs) enhance algorithm flexibility to handle diverse legislative document layouts worldwide. Processing a wide array of documents while ensuring robust results without overlooking critical sections is best achieved through a network of agents, each tasked with specific document-analyzing functions, working collaboratively to validate results.

Constructing a meaningful context for interpreting each requirement is essential. Therefore, dynamic and individualized context construction ensures accurate interpretation of all requirements mentioned in a document by AI agents. Traditionally, reviewing extracted or human-



1
FEV's systems engineering backbone C.U.B.E. provides context to AI use cases.



2
High level architecture of FEV's secure and efficient GenAI Hub. Also shown is a use case overview for the discipline requirements engineering and scheme of the requirements extraction use case.

generated requirements is time-consuming and error-prone. Automating this task with an AI-driven agent network dramatically improves the process in terms of time, costs, and quality. For a typical specification with 100,000 requirements, review effort is reduced from approximately four months to just four weeks, resulting in a 75% efficiency gain. The AI system checks legacy requirements for conformity, and suggests and applies improvements, significantly increasing overall requirement quality. This reduces downstream errors, enabling automated testing and validation. The return on investment is clear: with an implementation time of roughly 30 working days, the first reviewed specification with 100,000 requirements already offsets the cost.

By leveraging AI within structured frameworks like C.U.B.E. and GenAI Hub, FEV is driving cost-efficient and shortened development cycles, paving the way for a data-driven, AI-powered future in engineering.

Conclusion

The FEV GenAI Hub represents a significant advancement in the integration of artificial intelligence within the engineering sector. By addressing the challenges of data management, scalability, and practical application, FEV's systems engineering solution C.U.B.E. and the GenAI Hub platform provide a robust framework for leveraging AI to enhance both product development and internal processes. The strategic identification and prioritization of AI use cases, such as AI-driven requirements engineering, demonstrate the tangible benefits of AI in improving efficiency, reducing costs, and increasing overall quality. As AI continues to drive innovation, platforms like the GenAI Hub will be essential for companies looking to achieve cost-efficient, accelerated development cycles, ultimately paving the way for a more data-driven and AI-powered future in engineering.

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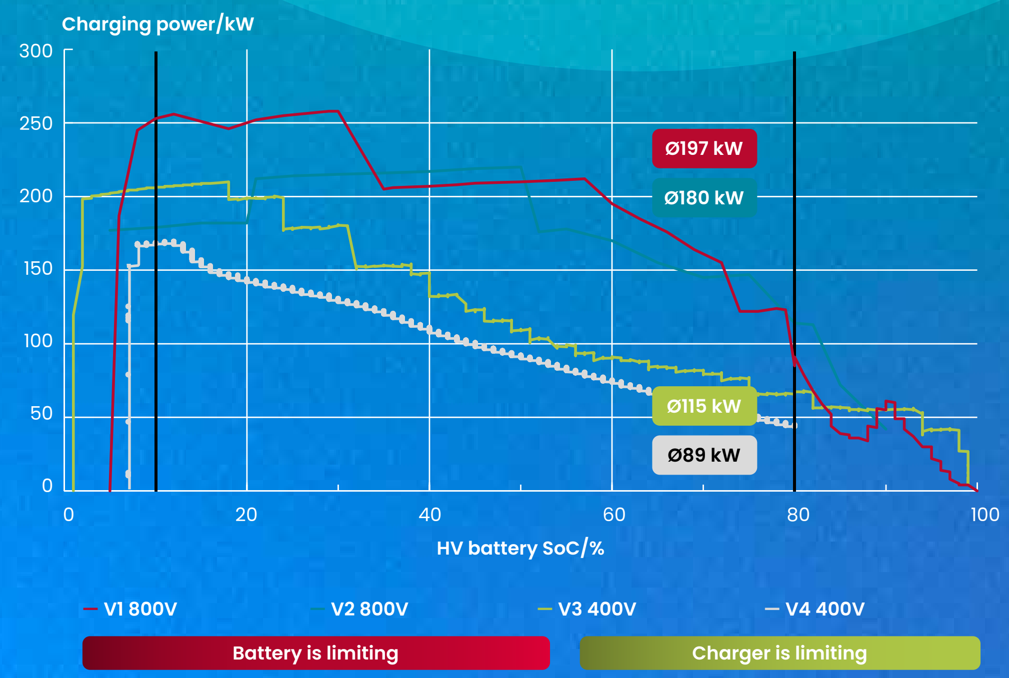
#2
Faster forward – The road to sub-10-minute charging

Although battery electric vehicles (BEV) continue to rise in popularity, barriers to widespread adoption remain. In the category of vehicle attributes, charging times are a frequent concern of many potential EV owners. Regardless of whether the available kWh are sufficient to commute for a whole week – until the point that recharging achieves some parity with conventional refueling, many consumers will continue to reject pure BEV options. To increase market acceptance, a formulated target by the key players in the industry is a fast-charging time of less than 10 minutes to bring the state of charge (SOC) of the battery from 10% to 80%. The required charging duration of a BEV is significantly influenced by several boundary conditions.

The boundary conditions to consider for fast charging include the start SOC, where a lower SoC is beneficial to utilize the particularly high charging capability at low in the range of 10% SoC to approximately 40% SOC. Further, the end SoC of fast charging protocols, which typically is around 80%, is determined by the onset of derating due to reaching the upper limit of the system voltage.

1
Comparison of charging speeds.



Further boundary conditions are set by the battery cell chemistry and the cell design, which have a strong influence on the achievable charge rate. The trade-offs to be made between energy density, cycle life and charge rate capability require that the battery cell design is tailored to the exact range, charge and lifetime requirements of the vehicle. To enable a long lifetime, keeping the battery cell temperature in the optimal range during fast charging is necessary. To this end, a sophisticated thermal system design and optimal control of the thermal preconditioning function are crucial.

Additionally, the type of electric vehicle supply equipment (EVSE) used plays a role, with charging power being limited by the capabilities of the 400V charging system. On-board DC-DC conversion can also limit performance. Figure 1 shows example charging profiles of a 70 kW reference vehicle from the FEV benchmarking program.

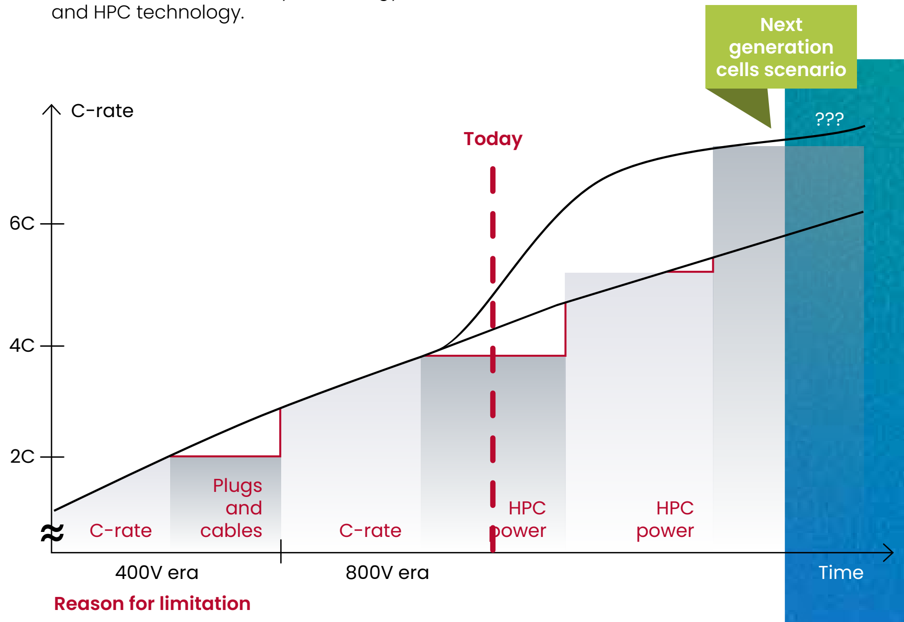
Motivation

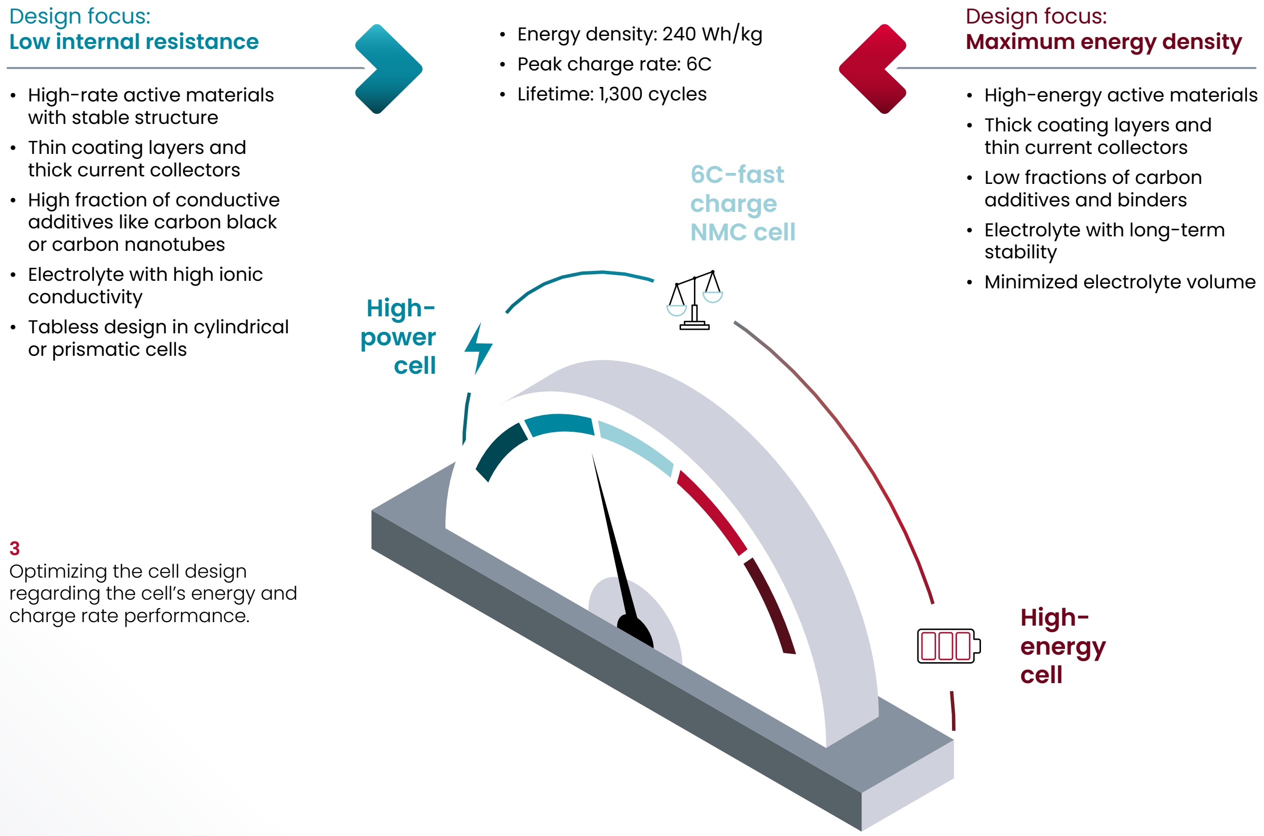
Customers expect highway charging stops to take less than 10 minutes, ideally charging from 10% to at least 80% SOC. To define an optimal charging system, including both infrastructure and vehicle aspects, several questions need to be addressed: What are the possible bottlenecks? What is the optimal system voltage? How can backward compatibility be guaranteed? Due to the complexity of the charging system, a solution can only be found through consistent, interdisciplinary cooperation among experts in charging infrastructure and BEV technology. The necessary competencies include E/E and high voltage architectures, thermal systems, controls, battery systems, and battery cells.

Historical context

The evolution of charging technology can be divided into two eras. In the 400V era, charging power was initially constrained by the rate at which high-energy battery cells could be charged or discharged relative to their capacity, a measure known as C-rate – and later by the limitations of 400V high power charging (HPC) systems. To increase charging power within the maximum current limitations and to match battery cell capabilities, 800V charging technology has been established. The power of 800V charging devices has continuously increased from 150 kW to 400 kW. In parallel, battery cell technology has rapidly evolved, and the upcoming 6C cell technology is expected to be a game-changer for further improving charging performance.

2
The race between battery technology and HPC technology.





3
Optimizing the cell design regarding the cell's energy and charge rate performance.

6C battery cell technology

Battery cell design can be optimized to achieve a balance between energy and power. State-of-the-art research has identified 6C fast-charging NMC cells as an optimal solution, provided a sufficiently efficient cooling system is used. High power cells focus on low internal resistance, using high-rate active materials with stable structures, thin coating layers, thick current collectors, and a high portion of conductive additives like carbon black or carbon nanotubes.

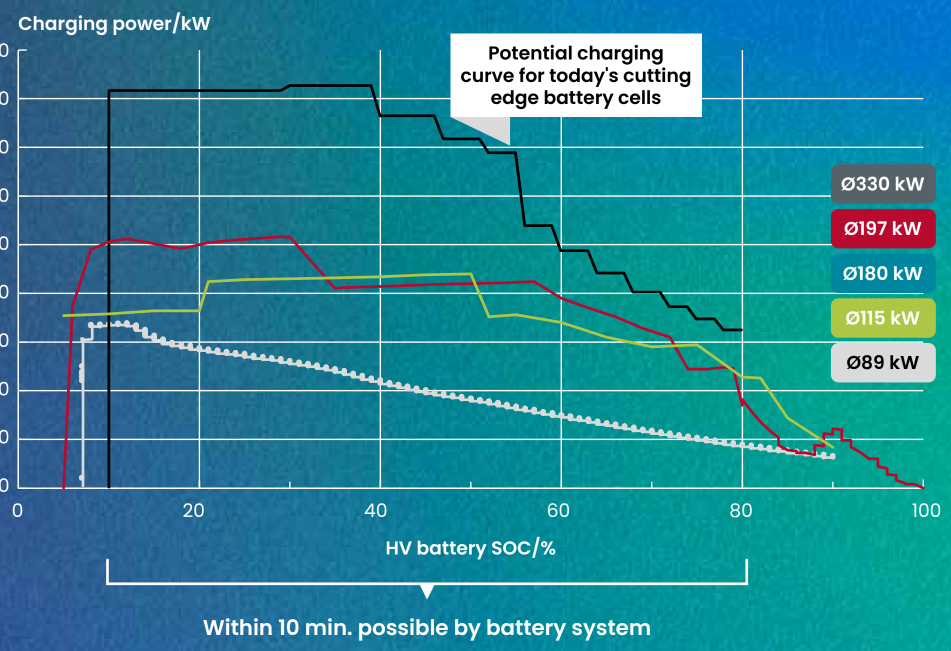
Electrolytes with high ionic conductivity are one of the key enablers of high rate capability. Tabless current collector designs in cylindrical or prismatic cells are also used to minimize the internal resistance of the battery cell. In contrast, high energy cells prioritize maximum energy density with high-energy active materials, thick coating layers, thin current collectors, and electrolytes prioritizing long-term stability over rate capability. The 6C cells are optimized for an energy density of 240 Wh/kg, a peak charge rate of 6C, a lifetime of 1,300 cycles, which at present day represents a suitable balance in terms of driving range, charge duration, and vehicle lifetime for the BEV use case of today.

Charging system potential study

FEV conducted a simulation study to determine the realistic potential to reduce charging time. The study investigated 6C cells from three manufacturers, using a 70 kWh vehicle as the baseline. Even with this baseline, the flat top area exceeds the 400 kW limitation of the current state-of-the-art charging infrastructure.

The bottle-neck: Charging infrastructure

To fully utilize modern battery cell technology and reduce charging time, several strategies can be explored:



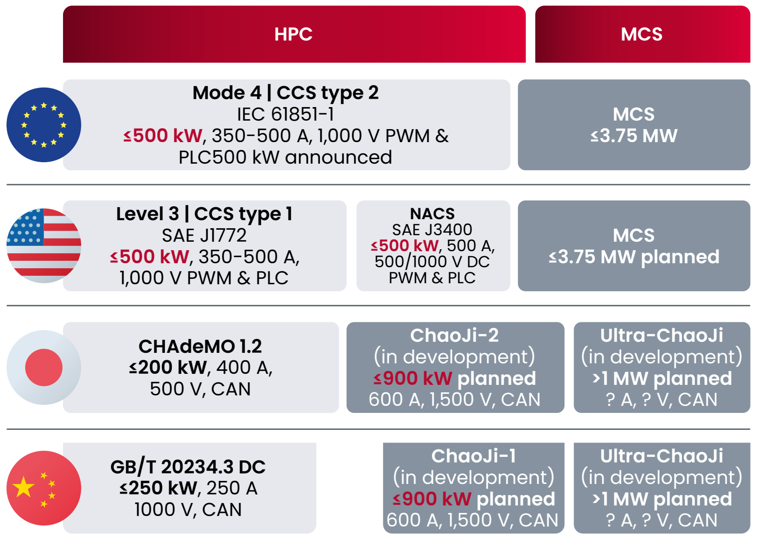
4
New battery cell technology with up to 6C are a game changer for charging performance.

1. Utilizing existing standards

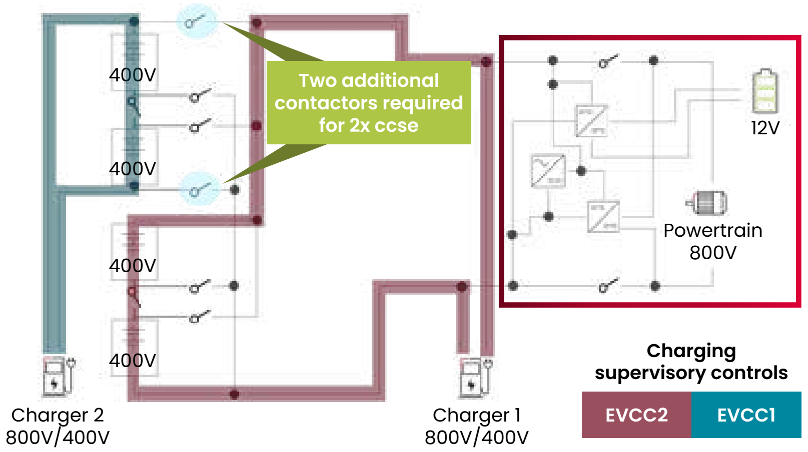
The boundary conditions in Europe with the combined charging system (CCS) type 2 and in North America with CCS type 1 and NACS are comparable. Both standards support a maximum charging power of 500A and an upper voltage of 1,000V. In Asia, the future ChaoJi standardization will exceed European and American standards with 900 kW (600A and 1,500V). However, due to the continued widespread use of 400V vehicles, backward compatibility of the charging infrastructure must always be guaranteed. The system voltage of the DC link in state-of-the-art 800V vehicles is often limited to 850V, preventing full utilization of ChaoJi's potential.

2. Megawatt charging system (MCS)

The MCS standard, designed for non-passenger cars, supports up to 3.75 MW with 1,250V and 3kA maximum performance. The plugs and connectors are robust and designed for high current charging of heavy-duty and bus applications. To use MCS in passenger cars, voltage conversion close to the battery



5
Future HPC will support >=500kW with CCS2/NACS/ChaoJi which is still the bottleneck for available battery technology.



6
Improving charging time while keeping compatibility.

»Customers expect highway charging stops to take less than 10 minutes, ideally from 10% to at least 80% SOC.«

is necessary to maintain the system voltage of the HV auxiliary units. Additionally, a second MCS charging socket would be required. Due to low distribution and limited public accessibility for cars, comprehensive integration of MCS is impractical. A parallel CCS2/NACS system would be necessary for backward compatibility.

3. Parallel charging

Parallel charging using multiple high-performance chargers is an unconventional yet promising approach for automotive applications. In parallel double charging, the vehicle is equipped with two charging ports, providing comfort advantages and easier access to charging stations. During the charging process, the battery is divided into two independent 800V strings by an extended switching matrix, each charged via one charging station. One string also supplies the necessary HV systems for parallel charging. An overlay control ensures even charging of the two battery halves, preventing significant differences in open circuit voltage (OCV). To ensure backward compatibility, the battery pack is divided into four 400V modules. The extended switching matrix can realize the following states:

- **400V compatibility single mode:** Suitable for charging at older 400V HPCs
- **800V single mode:** For charging at an 800V HPC
- **800V double charging:** For double charging, limited to battery system power
- **400V double charging:** For 400V double charging, limited to double HPC power

Another advantage of the modular battery concept is the possibility of residual availability in the event of a partial battery pack failure, allowing the vehicle to be charged and operated to a limited extent.

Recently, the Chinese manufacturer BYD announced that it will enable megawatt charging with 10C Blade batteries in its "Tang L" and "Han L" vehicles. This will also involve a "dual gun charging" concept. The promised performance is achieved through pulse heating and proprietary BYD charging stations with 225 kWh buffer batteries. The 10C charging power will be enabled under optimal conditions for 30 seconds. Another challenge by the demonstrated concept is the significantly higher costs of the SiC charging stations.

Conclusion

Achieving charging durations of less than 10 minutes requires a multifaceted approach involving advanced battery cell technology, optimized thermal systems, and innovative charging infrastructure solutions. By leveraging the potential of 6C battery cells and exploring options like utilizing existing standards, adopting the megawatt charging system, and implementing parallel charging, the path towards ultra-fast charging can be realized. Interdisciplinary cooperation among experts is essential to overcome the complexities and ensure a seamless transition to faster charging times for BEVs.

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#3 From cells to systems – How BMS unlocks ***next-gen battery performance***

This article explores the strategies and innovations required to unlock the potential of next generation cell chemistries and existing improved cell chemistries in the context of battery management systems (BMS). By addressing the unique challenges posed by these new chemistries, we aim to identify both the obstacles and opportunities to fully harness their potential improvements in energy density, cycle life, safety, and costs. The full potential of these new cell chemistries can only be realized through advanced BMS solutions. These include control algorithms (SoX), efficient cell balancing, temperature management, and the integration of AI and cloud-based solutions. The accuracy of voltage, current, and temperature measurements, as well as the prediction accuracy of internal state models, is key to unlocking their full potential.

Through a detailed examination of state-of-the-art BMS algorithms, this article offers valuable insights into which adjustments to current algorithms are necessary to accommodate new cell chemistries. Figure 1 (page 18) shows FEV's solutions for the state estimation functions. Depending on the cell chemistry and application, different methods are used to achieve the best possible result. This analysis primarily focuses on the impacts of new cell chemistries on the state of charge and state of health (SoC/SoH) estimation solutions. However, it should not be forgotten that for the safe and reliable operation of the new cell chemistries, the existing methods for early fault detection must also be adapted or, if necessary, extended by further robust detection mechanisms. Furthermore, the State of Power (SoP) algorithms, which ensure safe and efficient operation of the battery within its tolerances, must also be analysed in terms of their efficiency and aging effects. Optimizing charging time without placing excessive stress on the cells is of central importance for all chemistries. Efficiently controlled thermal monitoring and preconditioning of the battery plays an important role here. However, advanced charging algorithms, such as anode-controlled charging, are also becoming more significant.

1
Exemplary presentation of possible features that a BMS must evaluate and list of possible methods for the evaluation.

	Liquid electrolyte			Liquid, semi or full solid-state		Liquid electrolyte
Chemistry	NMC/NCA NCMA	LFP LMFP	LTO LNB	High silicon/ full silicon	Li-metal	Na-ion
Cathode (+)	$LiNi_xCo_yMn_zO_2$/ $LiNi_xCo_yAl_zO_2$	$LiFePO_4$ $Li(Fe, Mn)PO_4$	$LiNi_xCo_yMn_zO_2$ or LFP	NMC/NCA/NMCA	NMC/NCA/NMCA	Prussian blue/ White or layered oxide or polyanionic
Anode (-)	Graphite 1)	Graphite	$Li_4Ti_5O_{12}$ or (Nb, Ti)-oxide 2)	Graphite + high Si 3) or 100% Si	Lithium metalor anode-free	Hard carbon
Energy	+	• ↗	–	+ +	+ +	• ↗
Power	+ ↗	• ↗	+	– ↗	– ↗	+ ↗
Lifetime	+	+ +	+ +	– ↗	– ↗	+ +
Safety	• ↗	+ +	+ +	– ↗	– ↗	+
Cost	•	+ ↗	•	– ↗	– ↗	• ↗
Comment	Currently the most employed cell chemistry for HEV/ PHEV. Increase of Si & Ni shares to raise energy density and power output	Affordable chemistry; LFP is being adopted by most manufacturers for entry- and mid-level EVs	Utilized in applications that require high performance at very low temp.; Mostly MHEV applications with low capacity & high power	Technology with high potential energy density; several battery manufacturers have announced developments of this technology	Technology with high potential energy density; several battery manufacturers have announced developments of this technology, challenging production	First application in entry-level EVs; promising tech. for price-sensitive applications with moderate energy density requirements
Maturity 2025 > 2028	High > Very high	High > Very high	Very high > Very high	Low > Medium	Low > Medium	Medium > High

+ + Excellent performance
+ Good performance
• Medium performance
– Low performance
↗ Improvements expected

No
Low
Medium
High
Very high

1) Anodes currently may also contain up to 8% of silicon
2) Typical niobium oxides for anodes include Nb2O5, LiNb2O6, Nb12Ti10O29, Nb3Ti3O11 (Wadsley-Roth crystal structures)
3) High silicon contents are considered above 20 wt% Si in a graphite-Si composite material

2
Overview of emerging cell chemistries.

New battery chemistries

The rapid evolution of battery cell technologies continues to transform the landscape of energy storage at an impressive pace. Sodium-ion batteries (SIB) are emerging as a viable alternative for cost-optimized applications such as entry-level battery electric vehicles. Simultaneously, significant advancements of the conventional lithium-ion battery cell are achieved by the introduction of new cell chemistries like the lithium iron manganese phosphate battery (LMFP). Furthermore, the class of solid-state batteries (SSB) continues to push the boundaries of the battery cell performance in terms of energy density, enabling driving ranges of more than 1,000 km on a single charge. Figure 2 provides a qualitative overview of emerging battery technologies and their performance.

While these developments are exciting for vehicle manufacturers and customers alike, the adoption of these new and modified chemistries introduces significant challenges for the battery system development, and in particular, the BMS. The BMS is crucial for monitoring performance, ensuring safety, and optimizing efficiency in energy storage systems. The emerging cell technologies differ from the conventional lithium iron phosphate battery (LFP) and nickel manganese cobalt oxide battery (NMC) in terms of voltage profiles, charge-discharge characteristics, thermal behavior, and degradation patterns. Figure 3 shows a comparison of the quasi-open circuit potential curves of the different cell chemistries.

These variations require further advancements in BMS algorithms, state estimation techniques, and control strategies. Developers must refine battery models, adapt SoC and SoH estimation methods, and enhance thermal management strategies to accommodate these new chemistries.

Exploring SoX estimation in BMS: Challenges and solutions with new cell chemistries

This section presents an overview of the most common methods for SoH and SoC out of FEV's algorithms used in the BMS. These are also evaluated in terms of their suitability for the new cell chemistries.

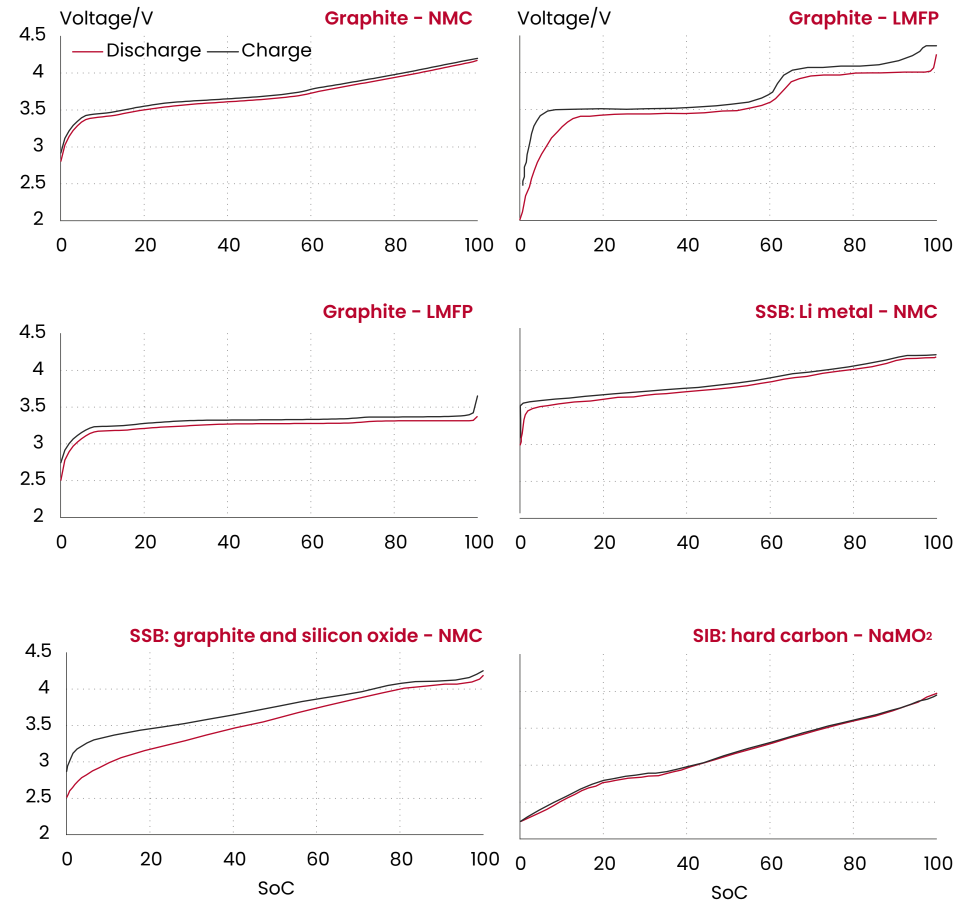
SoC estimation: Coulomb counting and Open Circuit Voltage (OCV) correction

Coulomb counting involves integrating the current over time to track the relative change in SoC, providing high precision during active battery use. However, it is prone to cumulative errors over extended periods. To mitigate this, OCV correction is employed during rest periods, where the battery's voltage stabilizes and reflects its true SoC.

Solid-state batteries, with their unique electrochemical properties, amplify these challenges due to their higher internal resistance and slower ion diffusion rates. To address this, FEV periodically applies OCV correction using real-time-clock (RTC) wake-up, quantifying the open circuit condition with respect to rest duration and temperature. This approach ensures reliable SoC estimation by accounting for the specific characteristics and operational conditions of solid-state batteries. However, determining the OCV for solid-state batteries can be complex due to their longer stabilization times and sensitivity to temperature variations.

Model-based SoC estimation

Since the method of Coulomb counting combined with SoC recalibration based on the OCV in LFP causes significant practical problems due to the very flat OCV curve, a model-based approach offers a suitable way to circumvent these issues.



3
Quasi OCV curves of some different battery cell chemistries.

»In battery system development, new and modified chemistries introduce significant challenges. Especially for the BMS, which is crucial for monitoring performance, ensuring safety, and optimizing system efficiency.«

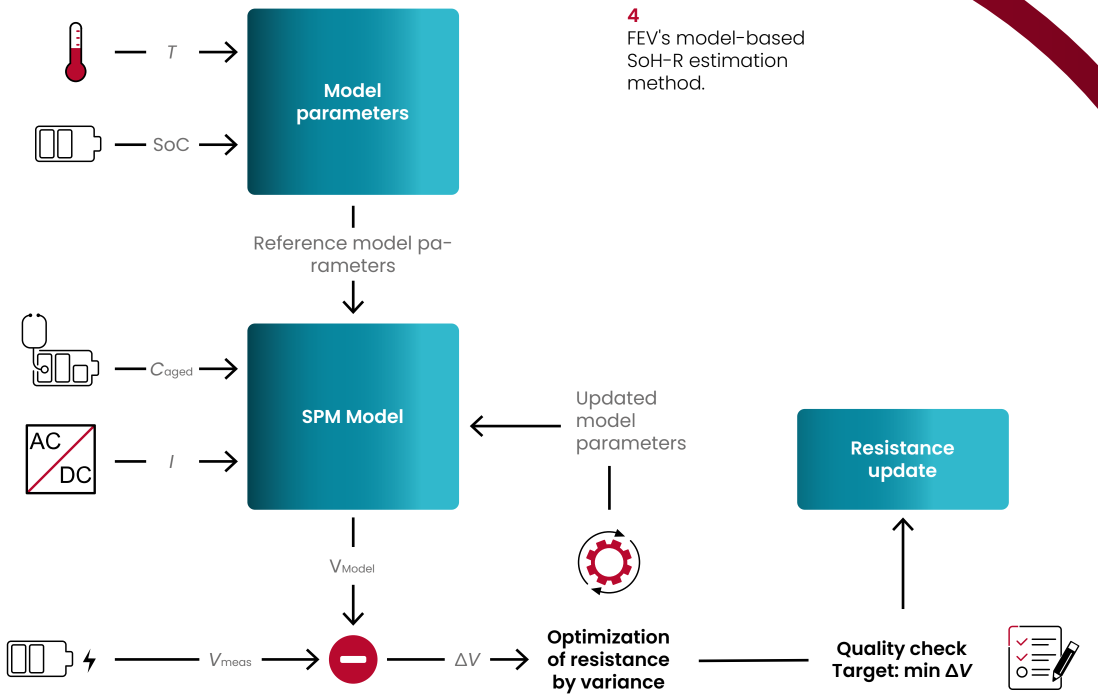
FEV applies the Kalman Filter (KF) approach for SoC estimation, utilizing various modeling techniques, ranging from equivalent circuit models (ECM) to single particle models (SPM). The battery modeling used in KF approaches faces several new challenges for solid-state batteries. Solid-state batteries tend to exhibit higher internal resistance compared to traditional NMC batteries. This increased resistance complicates the accurate representation of electrochemical processes within the SPM framework, requiring more sophisticated modeling techniques. Additionally, the ion diffusion rates in solid-state batteries are typically slower compared to conventional, liquid-electrolyte-based batteries. This affects the dynamic behavior of the battery, making it challenging to model the kinetics and transport phenomena accurately.

Another challenge is interphase formation. Solid-state batteries often experience contact loss and interphase formation at the solid electrolyte-electrode interfaces. These phenomena are less pronounced in NMC batteries and add complexity to the SPM modeling of solid-state batteries. Furthermore, solid-state batteries are highly sensitive to temperature variations, which can significantly impact their performance and SoC estimation. This sensitivity needs to be accurately captured in the SPM model to ensure reliable predictions.

Finally, the stability of solid electrolytes under various operating conditions is a critical challenge. Modeling these stability issues within the SPM framework requires detailed understanding and representation of the material properties. Addressing these challenges is essential for developing accurate and reliable SoC estimation methods for solid-state batteries.

SoH estimation

State of Health estimation is crucial for assessing the longevity and performance of lithium-ion batteries. Two primary indicators used for SoH estimation are internal resistance (SoH-R) and capacity (SoH-C). Internal resistance provides insights into the battery's electrochemical properties and degradation, as increased resistance often signifies aging and reduced efficiency. Capacity measurement, on the other hand, compares the current capacity to the original capacity, quantifying the loss of usable energy storage over time.



4
FEV's model-based SoH-R estimation method.

SoH-R estimation

Figure 4 illustrates the SPM model-based resistance estimation method. In this FEV approach, the expected cell voltage as a function of the current for the given operating condition of the battery is estimated using an SPM and compared with the actual measured cell voltage. The selection of the SPM parameters is done using characteristic maps, which have been calibrated with data from previously conducted cell bench tests. For each calculation step, the parameters are varied; and for each variation, the expected cell voltage is modeled and compared with the actual measured cell voltage. The goal is to find the variation with the smallest difference between the measured and modeled voltage. The determined variation then allows direct conclusions to be drawn about the internal resistance.

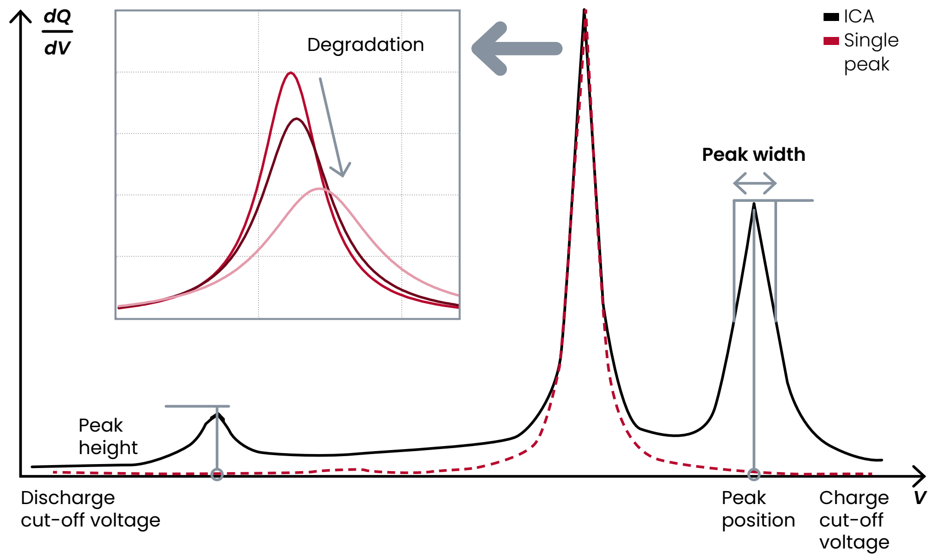
When it comes to solid-state batteries, the principles of SoH estimation remain similar, but the unique characteristics of these batteries introduce similar challenges for model-based SoH-R estimation methods as the previously explained model-based SoC estimation.

SoH-C estimation

The incremental capacity curve is one of the most frequently used health indicators in data-driven approaches for capacity estimation. The incremental capacity is obtained through the differentiation of the capacity voltage curve under a quasi-open circuit condition. Usually, there are three or four peaks in the differential curve, indicating different phase transition processes in the electrodes. The peak position, peak height, peak area, peak width, and peak slope are widely used as health indicators in the health state diagnosis, where the shift of peak position, decrease of peak height and area, vanishing of peaks due to overlapping and increase of peak width are common indicators of degradation that can be related to resistance increase and capacity loss as depicted in figure 5.

FEV applies the incremental capacity analysis (ICA) method, combining time series forecasting and classification based on the long short-term memory (LSTM) model, to perform SoH estimation within a short SoC range during the charging

5
ICA curve used for SoH-C estimation.



process. Additionally, FEV utilizes an ICA curve fitting method that employs multi-dimensional Gaussian or Lorentzian functions as basic functions to fit the peaks. The parameters in these basic functions indicate various peak features in the incremental capacity curve mentioned above.

However, the ICA-based method for SoH estimation faces several challenges when applied to solid-state batteries and LMFP batteries. For solid-state batteries, the primary challenge lies in accurately capturing the diffusion changes and resistance variations due to the solid-electrolyte interface. Resistance variations, often caused by interface potentials and imperfect contact between electrodes and solid electrolytes, can also affect the accuracy of SoH estimation

In the case of LMFP batteries, the unique electrochemical properties present additional complexities. These properties include higher voltage plateaus, lower electronic conductivity, and lithium-ion diffusivity, as well as potential manganese dissolution in the electrolyte. These factors can complicate the interpretation of the incremental capacity curves, necessitating further refinement of the ICA method to ensure reliable SoH estimation for these advanced battery chemistries.

Qualitative assessment of SoX estimation methods

In summary, figure 6 presents an overview of the most common SoX estimation methods in BMS, focusing on emerging new cell chemistries in terms of complexity and accuracy. To enhance understanding of the challenges, NMC and LFP cells, which are widely used in electric vehicles (EVs), are included to improve the comparison and highlight specific challenges associated with these chemistries.

Feature	Method	NMC		LFP		LFMP		SSB Graphite		Na-Ion	
		Accuracy	Complexity	Accuracy	Complexity	Accuracy	Complexity	Accuracy	Complexity	Accuracy	Complexity
SoC	CC + OCV	++	++	−	•	•	•	•	•	+	+
	SPM/ ECM + KF	+	−	+	−−	+	−−	+	−−	+	−
	Data driven (LSTM)	+	•	•	•	•	•	•	•	+	•
SoH-C	SoC-OCV vs. ah-counting	++	++	−	−	•	•	•	•	+	+
	Data driven (LSTM for ICA)	++	−	+	−	•	−	•	−	+	−
SoH-R	Pulse based	+	+	−	•	•	•	•	•	+	+
	SPM/ECM + KF	+	−	+	−−	+	−−	+	−−	+	−
Comments		• In principle, all methods are suitable and accurate • Almost no hysteresis in OCV		• Voltage hysteresis for whole SoC-range • Very flat OCV for almost whole useable SoC range; Evaluation of OCV for SoC determination difficult		• Partially very high hysteresis • Shape of OCV depends highly on used Manganese • Flat OCV for wide range of SoC		• Very high voltage hysteresis at low SoC range • Model parameterization difficult; High temperature dependency • High decrease of available capacity due to high resistance at low SoC		• Useability and accuracy of methods quite similar to NMC • Almost no hysteresis in OCV; but for low SoC	

6
Qualitative assessment of various SoX estimation methods for determining specific features in respective cell chemistries. The table only shows a concise summary of all methods and features.

++ Accuracy: very high; complexity: very low
\+ Accuracy: high; complexity: low
• Accuracy: moderate; complexity: moderate
− Accuracy: low; complexity: high
−− Accuracy: very low; complexity: very high

Conclusion

The future of BMS is poised to evolve significantly with the advent of new cell chemistries. To manage these technologies effectively, BMS must adapt by integrating advanced technical solutions. Key trends include the incorporation of AI and machine learning, as well as providing enhanced computational power to embedded BMS hardware to accommodate more sophisticated battery models and advanced estimation methods. Data-driven approaches can also be used with the new cell chemistries to reliably estimate the battery condition and thus make a valuable contribution to optimizing performance and service life. Furthermore, a cloud-based implementation of algorithms for non-time-critical battery conditions, such as SoH, can also be used as a possible methodology to minimize the computing power requirements of the BMS.

Regardless of whether a cloud-based or embedded implementation is used, the methods developed by FEV provide a strong foundation for SoX determination in future cell chemistries, as they can be adapted to specific cell characteristics.The company is continuously working on the further development and adaptation of these methods to enable and optimize their future use.

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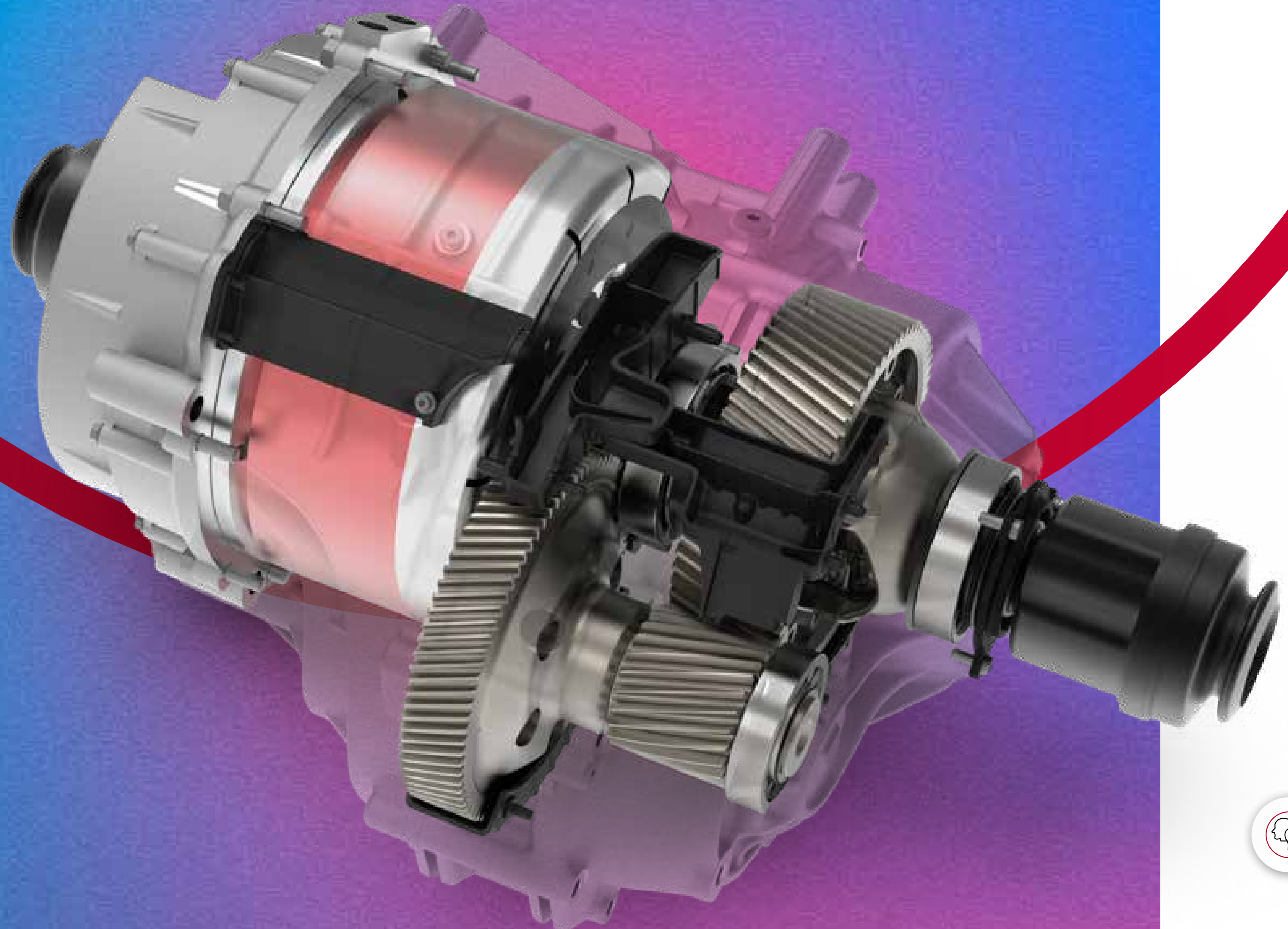
#4 Electrified excellence – FEV's ***high-performance EDU*** solutions



Electric vehicles (EVs) have claimed a considerable share of the automotive market. This trend is not limited to passenger cars but also many light duty commercial vehicles, such as delivery vans; and is now extending into the heavy truck and non-road machinery segments such as agricultural and construction equipment.

Regardless of the application, high efficiency as well as low cost and noise are among the most relevant development goals for the next generations of EVs. FEV has implemented a comprehensive tool chain to support customers in the development and optimization of electric powertrains including Electric Drive Units (EDUs). This article provides an insight into some of the EDU development fields in which FEV is operating.

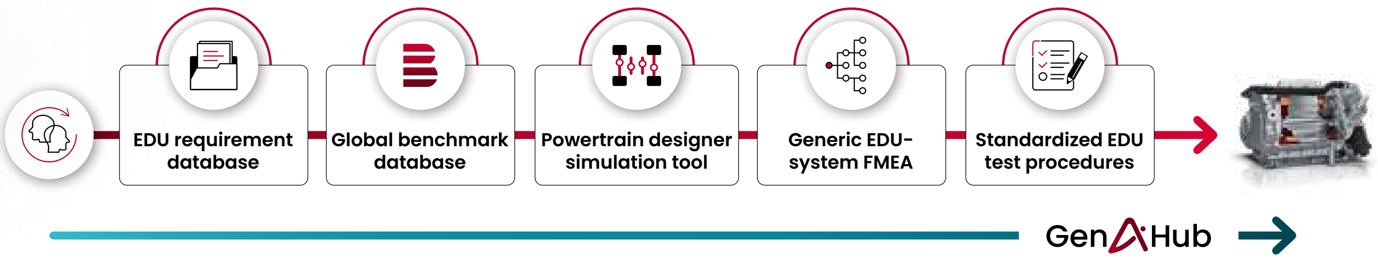
Development toolchain for electric drives optimization

The technology choice and right-sizing of an electric powertrain including the EDU is a complex task involving numerous parameters. These include, for example, the size and type of the electric motor, the architecture and gear ratio of the reducer, and the inverter technology; all down to the most minute detail.

To define the optimum configuration of the EDU and its components for a given application, FEV offers a development toolchain built on different pillars (figure 1).

The EDU requirement database includes a large number of generic system-level requirements for both hardware and software. These can be exported in various formats to ensure compatibility with leading software products.

1
FEV toolchain to define an optimum EDU configuration.



The global benchmark database contains detailed specifications and analysis results for vehicles, systems and components. This database allows the definition of a solution space for future EDUs, which can then be evaluated in a simulation environment.

The simulation environment, Powertrain Designer, evaluates the energy consumption, performance and cost of powertrain options including operating strategies using a backward simulation algorithm and nested optimization.

Throughout the development, FEV adopts a systematic approach based on failure mode and effect analysis (FMEA) to identify potential design failures, assess their impact, and implement corrective actions. The primary goal is to enhance product reliability and safety, starting as early as the concept phase.

Directly linked to the actions in the FMEA, FEV has developed a standardized test case and validation plan on the system and component level. It covers all electrical and mechanical subsystems and their characteristics and failure mechanisms.

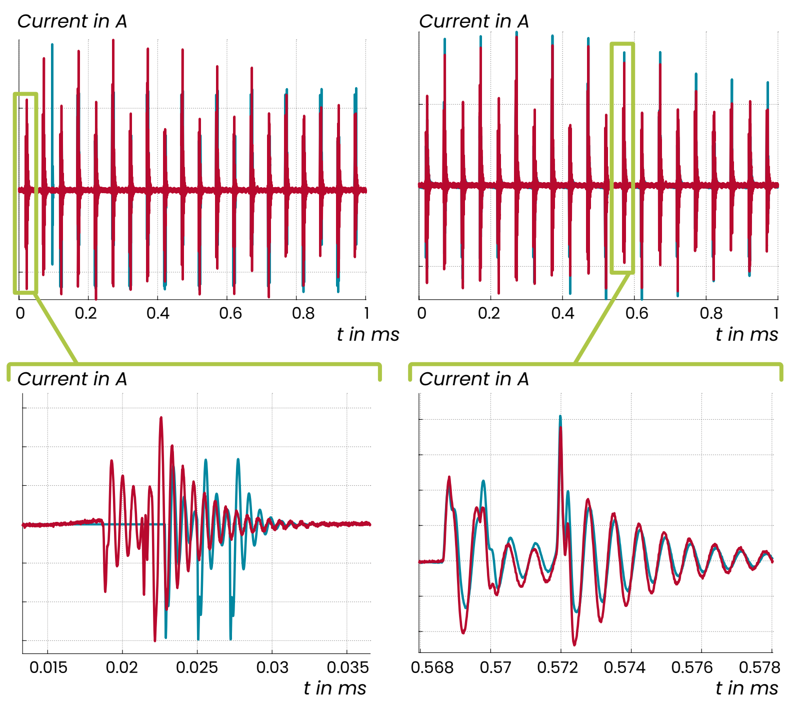
The recently launched and in-house developed FEV GenAI Hub (see article on page 6) marks a significant step forward by seamlessly linking the aforementioned tools and databases to significantly speed up the development process. For example, generic requirements from the database can be automatically tailored to customer and market needs.

Subsequently, system and component specifications gathered in the benchmark database can be automatically compiled as input for the simulation of the EDU system in the Powertrain Designer tool. By feeding the FMEA and generic test cases with the project boundaries and the auto-filtered requirements, a customer-specific validation catalogue can be created, covering both digital and physical validation, with an ever-increasing focus on digital validation to reduce development times.

Modeling of bearing currents

Bearing failures are a common failure mechanism of electric motors. Among the different causes of bearing failures, bearing currents, caused by the pulse-width modulation of inverters, are gaining more relevance in the automotive industry due to the trends towards higher battery voltages and higher switching frequencies. These bearing currents cause local temperature increases, leading to the abrasion of metallic bearing race surfaces and degradation of the lubricant, which ultimately results in bearing failure.

FEV deals with both the modeling and the measurement of bearing currents in electric powertrains. A comprehensive simulation toolchain, comprised of finite element analysis, high-frequency modeling, and frequency- and time-domain system simulation, is employed to predict the bearing currents in electric powertrains based on dimensions, operating parameters, and material properties. As shown in figure 2, where simulation and measurement results of non-drive end bearing currents in a state-of-the-art 800V oil-cooled electric powertrain are compared, the simulation toolchain exhibits exceptional accuracy. Thus, it can be used to define bearing current mitigation strategies in an early development stage, as well as to support troubleshooting activities.



2
Comparison of simulation and measurement results.

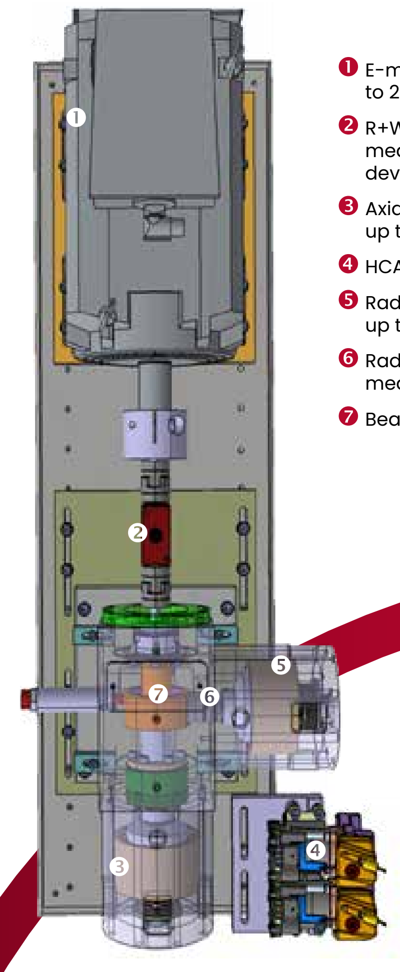
High speed bearing test bench

The increasing maximum speed of electric traction machines is a major challenge especially for the bearings and the lubrication system of an EDU. New types of oil and additives are being developed to ensure sufficient lubrication and cooling, in order to fulfill lifetime duty and efficiency requirements. These new boundary conditions require adjustments to bearing test benches and test procedures. In response, FEV has developed an advanced bearing test bench.

It allows the simultaneous testing of up to two bearings at high-speed and high-load conditions, including highly dynamic overload and misuse, as well as the investigation of various lubrication concepts and parameters.

The maximum speed is currently 24,000 rpm. Radial loads up to 22 kN and axial loads up to 44 kN are applied hydraulically and measured with load cells. Temperature and health monitoring are also implemented, as well as video analysis with a high-speed camera.

In an ongoing project, FEV is also adding the capability to test the influence of defined bearing currents on bearing functionality and durability.



1 E-motor, up to 24,000 rpm
2 R+W torque measurement device +- 30v Nm
3 Axial load apply up to 44 kN
4 HCA
5 Radial load apply up to 22 kN
6 Radial load measurement
7 Bearing in slide

3
Top view of FEV's high-speed bearing test bench.

Investigation of the noise and vibration behavior of electric machines using 3D-laser-Doppler-vibrometry

The noise and vibration behavior of electric machines is an important design and quality criterion, especially for mobile applications. For accurate NVH simulation, the structural dynamic damping of electric machines plays a decisive role.

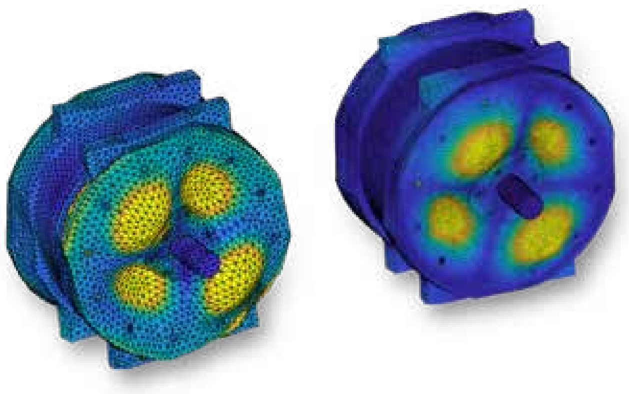
In most cases, time-consuming experimental modal analysis is conducted to determine damping ratios. However, achieving sufficient excitation in experimental modal analysis is often challenging. Furthermore, the damping parameters are only valid for the geometries at hand, and no predictions can be made for other machines on this basis.

To solve this problem, FEV applies a new approach to describe the structural dynamic damping of electric machines. The key idea is to model the individual physical damping effects using an energy-based description according to VDI 3830. Through this it is possible to model not only the internal damping due to material and interface damping, but also external damping effects, such as air-borne-sound radiation.

To apply this approach to a given machine, its electromagnetic forces are calculated by a 2D transient finite element simulation. The forces are then transformed to frequency domain and applied to the structural dynamic model. Together with calculated modal damping, the structural dynamic response of the machine can be calculated.

In order to verify the results, test bench measurements at constant operating points have been performed. The number of measurement points that can be implemented with conventional accelerometers is limited; however, optical 3D-scanning-laser-Doppler-vibrometry overcomes this limitation. For the first time, this optical measurement approach offers the possibility to realize a spatial resolution similar to the density of the FE-mesh, sufficient for the complete audible frequency spectrum. Exemplary simulation and measurement results with a grid of approx. 7,000 measurement points are shown in figure 4.

A comparison for the operation deflection shapes has been performed and shows good correlation. With sufficient correlation data, precise NVH predictions will be possible in an early development phase based on simulated damping characteristics alone. Ongoing work includes the prediction of radiated sound based on the high-resolution surface vibration data.

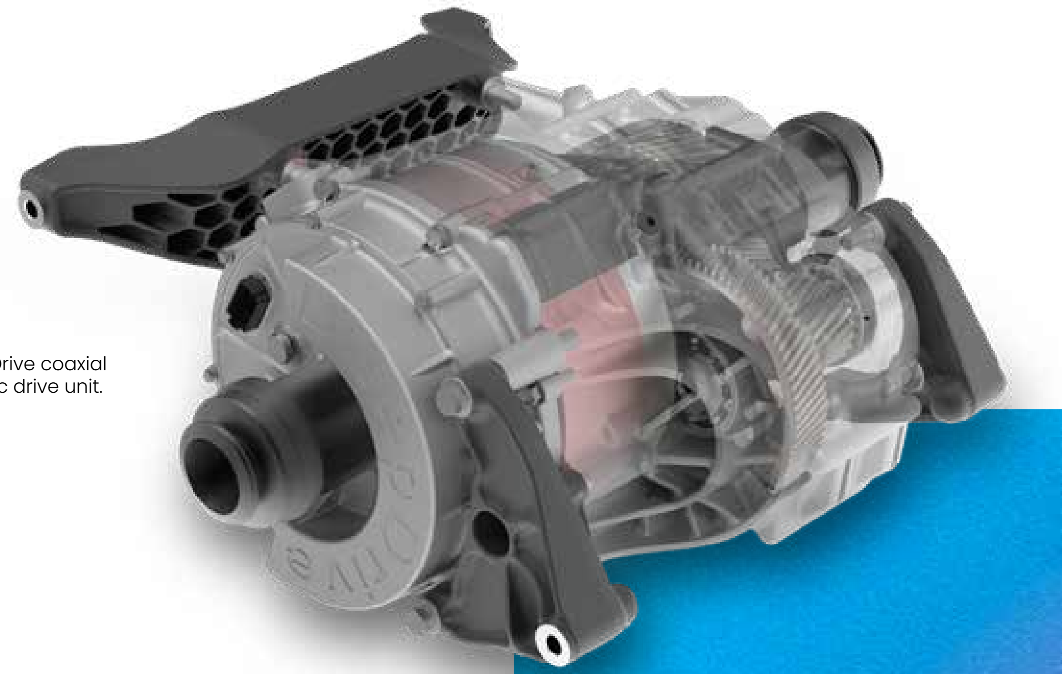


4
Deflection shapes in measurement (left) and simulation (right).

Innovative electric powertrains in cooperation with DeepDrive

The Munich-based start-up, DeepDrive, has developed, validated, and patented a novel electric machine based on a dual-rotor radial flux arrangement which offers two main advantages: a significant increase in efficiency and a reduction in component costs due to less raw material use and simplified manufacturing processes. For most applications, the dual-rotor machine is combined with DeepDrive's multi-level SiC inverter, which is coaxially arranged and directly attached to the electric machine's stator, sharing a joint water-cooling jacket. This allows compact and efficient electric powertrains to be created at attractive costs.

One of DeepDrive's key focus areas is in-wheel motors, which significantly benefit from the high torque and power density of the motor and inverter technology. However, the field of potential applications in the world of electric powertrains is much larger.



5
DeepDrive coaxial electric drive unit.

In an initial collaboration with FEV, a single-speed electric drive unit has been developed. Just like the underlying machine technology, the entire drive has been optimized for efficiency and low cost. Optionally, the unit incorporates FEV's unique roller-based park lock system, which can be neatly packaged into the rotors of the electric machine, and which eliminates the functional drawbacks found in conventional park lock systems.

DeepDrive and FEV are now collaborating to apply DeepDrive's technology to generator units for range-extended electric vehicles (REEVs), following an emerging trend in the automotive industry. High torque and power at moderate speeds are an ideal match for modern, high-efficiency combustion engines. The short length of the machine and the attached, coaxial inverter with a single joint water-cooling jacket are very attractive in terms of packaging and integration.

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Conclusion

FEV is at the forefront of next-generation electric drive unit development, leveraging cutting-edge tools, AI-driven optimization, and advanced testing methodologies to enhance efficiency, reliability, and cost-effectiveness. By integrating a comprehensive development toolchain, including the FEV GenAI platform, FEV streamlines the design process, ensuring expertly tailored and high-performing powertrains.

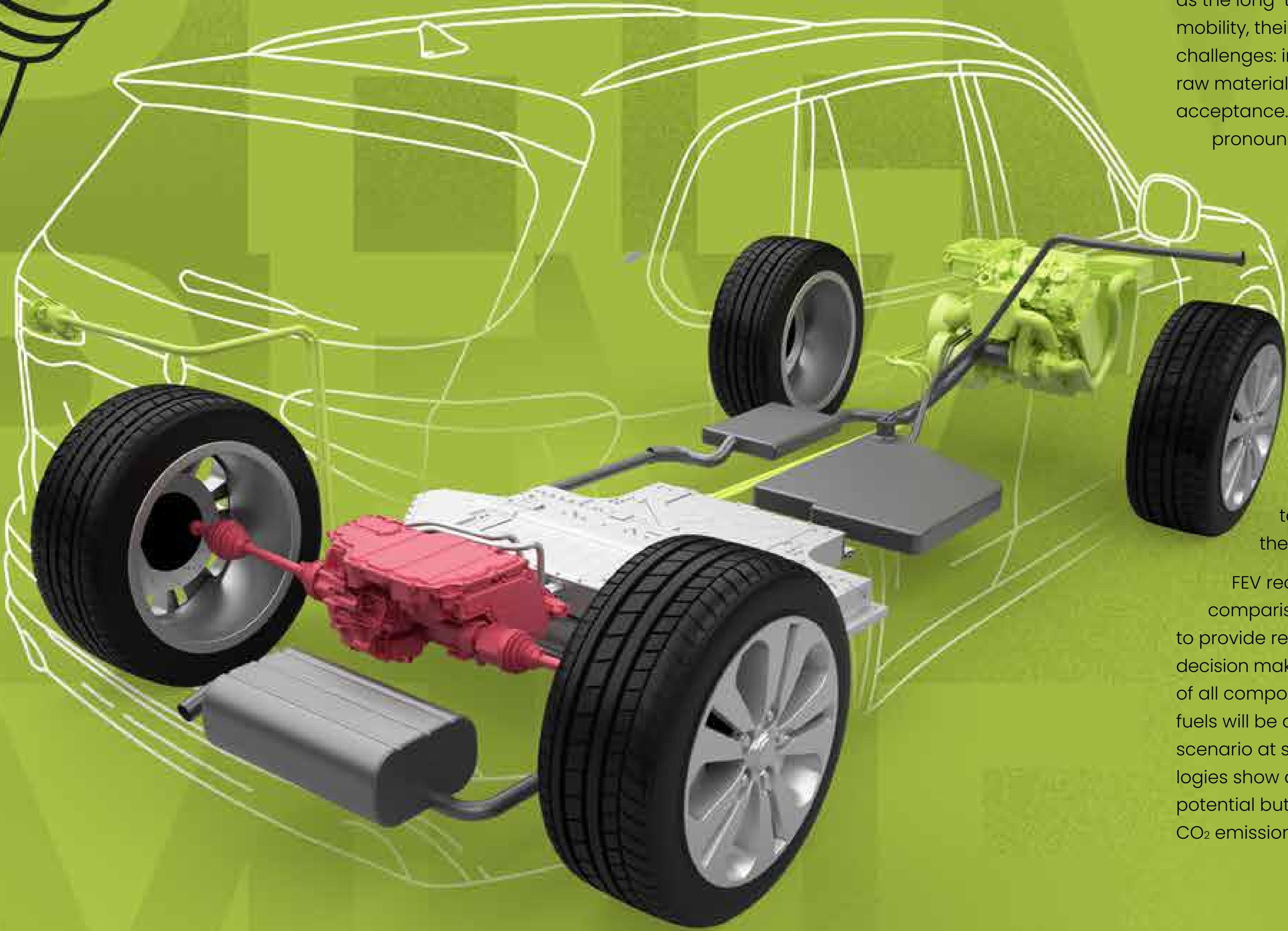
Innovations in bearing current simulation and testing, high-speed bearing test benches, and NVH analysis with 3D-laser-Doppler-vibrometry are driving improvements in durability, efficiency, and noise reduction. Additionally, collaborations with DeepDrive are pushing the boundaries of electric machine design, delivering compact and highly efficient solutions for various EV applications, including range extenders.

By combining advanced simulation techniques, systematic validation strategies, and breakthrough partnerships, FEV continues to shape the future of electric mobility – delivering high-efficiency EDUs that meet the evolving demands of the industry.

#5
Hybrid BEVs – The smart evolution of electric drive

To achieve the ambitious targets of the Paris Climate Agreement and the IPCC's 1.5°C goal, global climate-relevant CO_2 emissions must be reduced. This transformation demands rapid and scalable solutions – particularly in the transport sector, which remains a major contributor to global emissions.

While battery electric vehicles (BEVs) are seen as the long-term cornerstone of defossilized mobility, their mass adoption still faces critical challenges: infrastructure limitations, high costs, raw material dependencies, and customer acceptance. These barriers are especially pronounced in non-urban and emerging markets. Against this backdrop, Hybrid BEVs (HyBEVs), also named range-extended electric vehicles (REEVs), offer a pragmatic and technically mature solution – combining the advantages of electric propulsion with the flexibility of combustion engines.

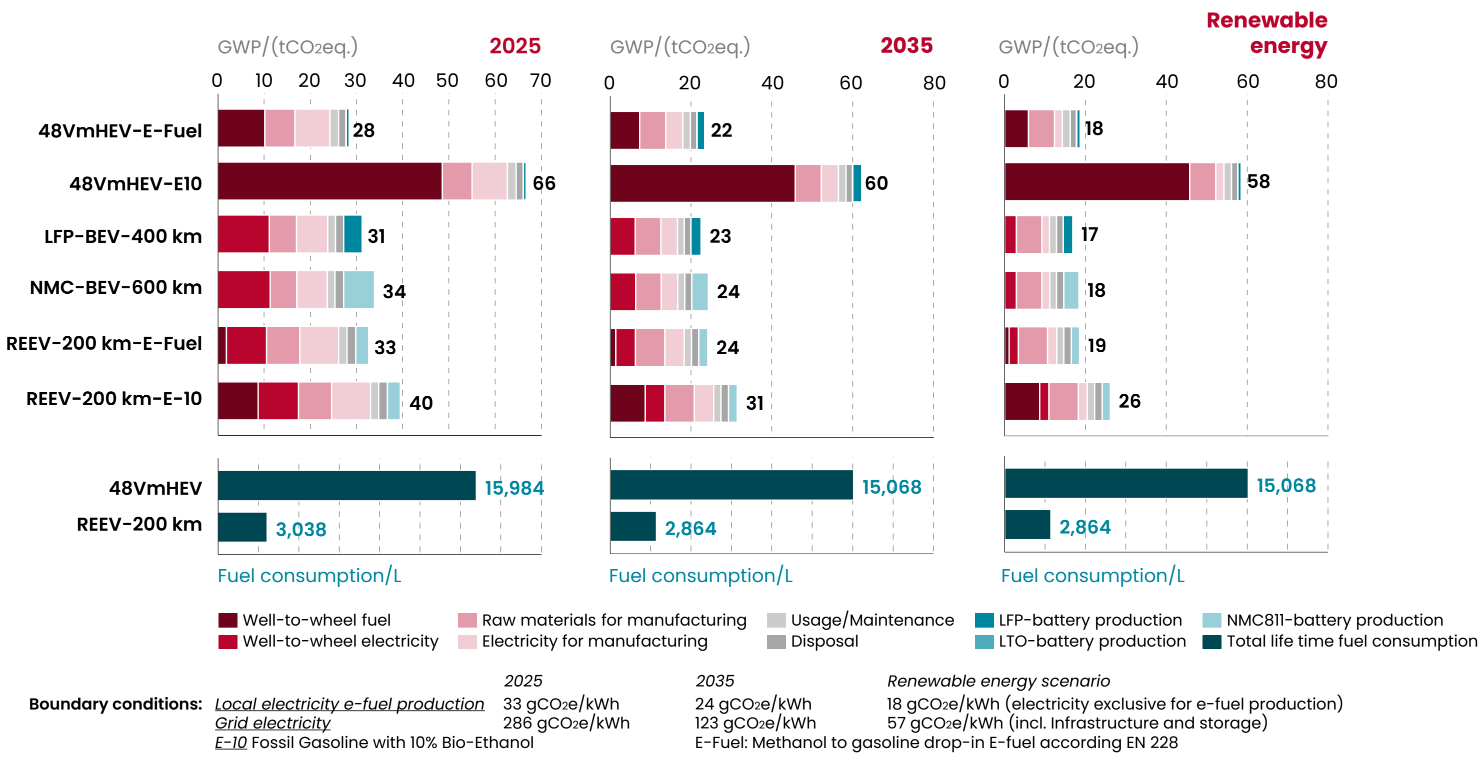


FEV recently conducted a comprehensive comparison of major propulsion technologies to provide relevant technical background for decision makers. Assuming that the production of all components, as well as the corresponding fuels will be driven by a fully renewable energy scenario at some point in the future, all technologies show a similar residual global warming potential but with a significant reduction in CO_2 emission compared to today.

Customer needs

Despite early adopters may be driven by a climate-friendly approach and also a technological curiosity, for the average user, costs and reliability are the main reasons for a vehicle purchasing decision. In the long run, the costs are in favor of the BEV. Driven by more and more decreasing battery achievable costs of 70 €/kWh today and an outlook towards 55 €/kWh in 2035 (figure 1, page 32), more and more attractively priced electric vehicles will come onto the market.

Looking at the reliability of BEV, range and charging are the key factors to customer acceptance. The actually needed driving ranges are distributed similarly worldwide. In Germany, for example, 97% of all daily needs are less than 200 km range and hence are covered by most available BEV today. Also, the PHEV/REEV in the above-mentioned LCA analysis have been chosen accordingly to cover this with an all-electric range of 200 km.



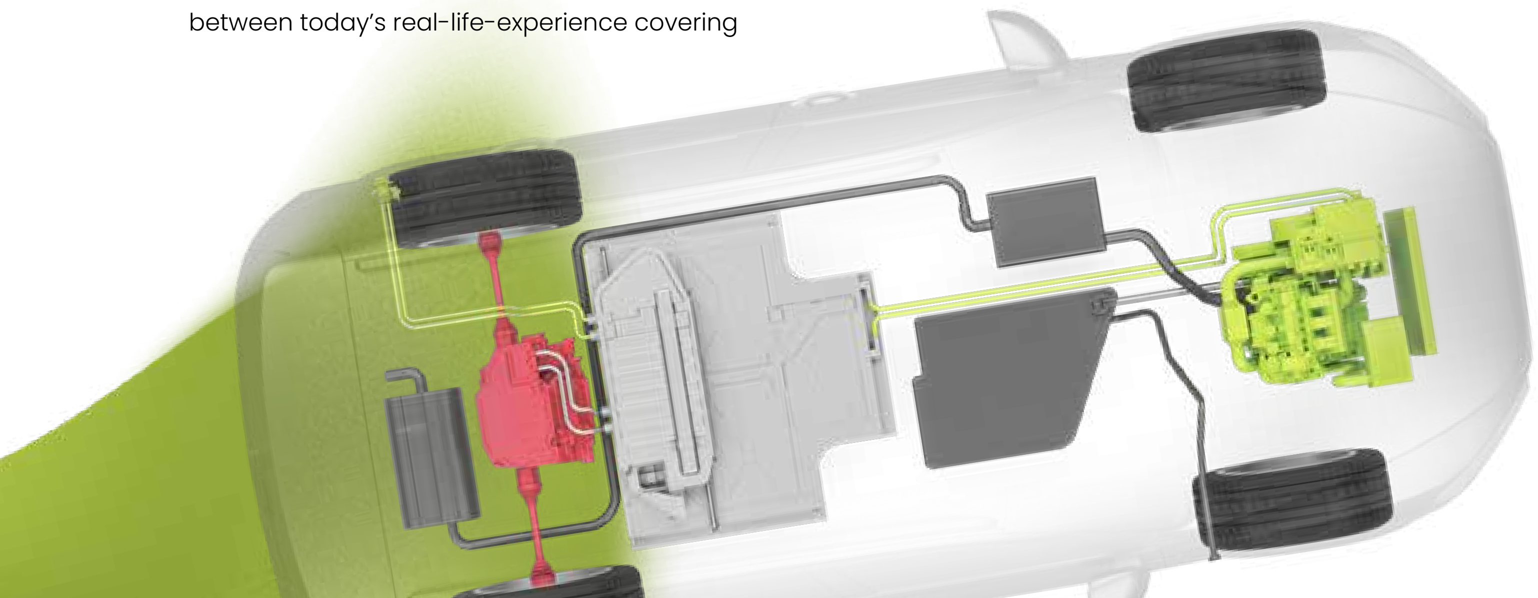
1
All powertrain concepts can reduce global warming similar, but e-fuel demand is significantly higher without electric driving.

Still, customer acceptance is also influenced by long-range travel requirements, as well as the speed and convenience of re-charging. The charging infrastructure is strongly growing and additionally supported by the European "automotive action plan", too. Charging performance is pushed further, as described from page 10 in this SPECTRUM.

Nevertheless, in today's reality even in Europe, charging an electric car is still far from being taken for granted in the same way as refueling, and a careful planning of upcoming charging stops is mandatory – also strongly depending on the area of Europe the driver is in.

Hence, from a customer point of view, additional alternatives are desired to bridge the gap between today's real-life-experience covering all driving scenarios and a not so far future where most likely these topics will not be a matter of discussion anymore at all.

Simply continuing with ICE vehicles and switching to regenerative fuels is not a viable solution either. There is a massive lack of availability of both eFuel and bio-LHC. Even if all productions sites planned today were realized, current legal requirements for 2035 couldn't be met. Since the transition from planning to production takes at least 8 to 10 years, it is evident that eFuel must be treated as a limited resource, and any scenario assuming widespread eFuel availability for all ICE-driven vehicles is highly unrealistic for the next decade and beyond.

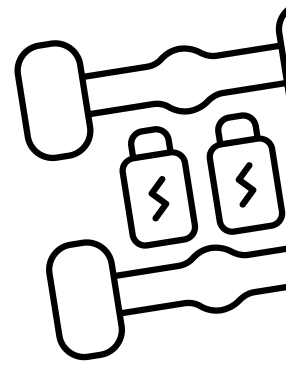


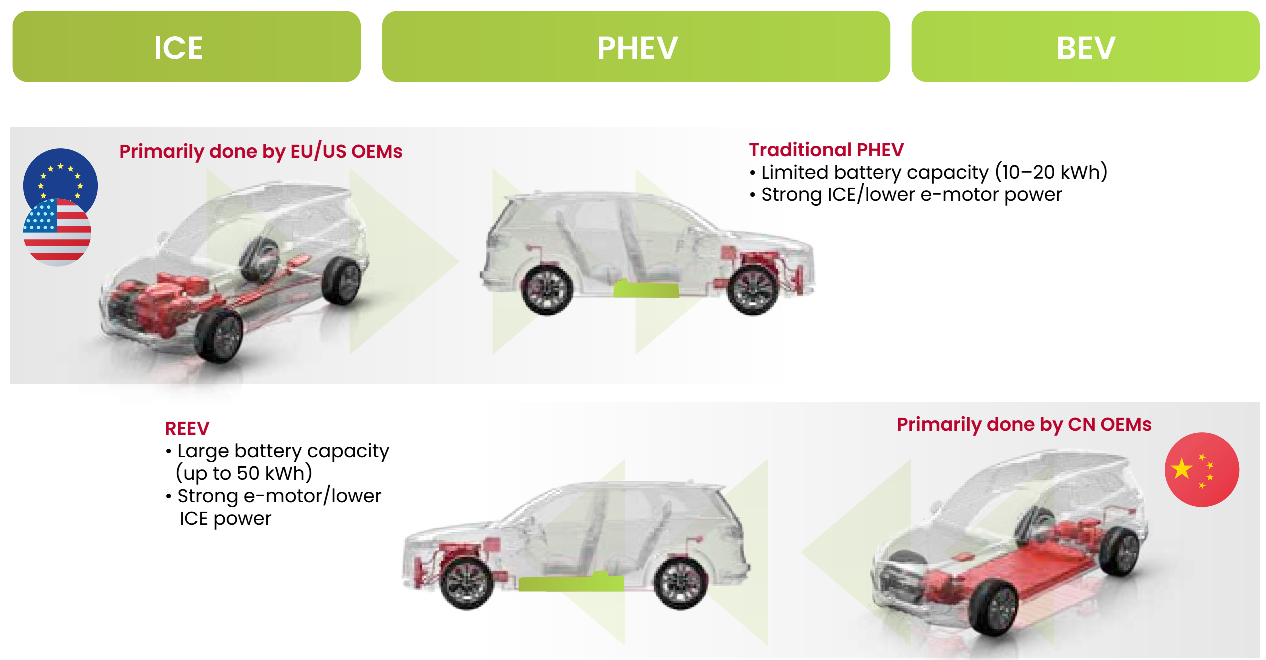
On the other hand, a fleet consisting of 80% BEV and 20% long-range PHEV or REEV using "conventional" fossil fuels would emit only 5.6g CO_2/km and require only 2.9% of the fuel compared to today's needs. Compared to the emission limit we are subject to today, this seems to be neglectable, at least for a while, if this buys enough time to enable the ramp-up of the large-scale production of eFuels as well as a European-wide, equally spread charging infrastructure.

Hybrid architectures

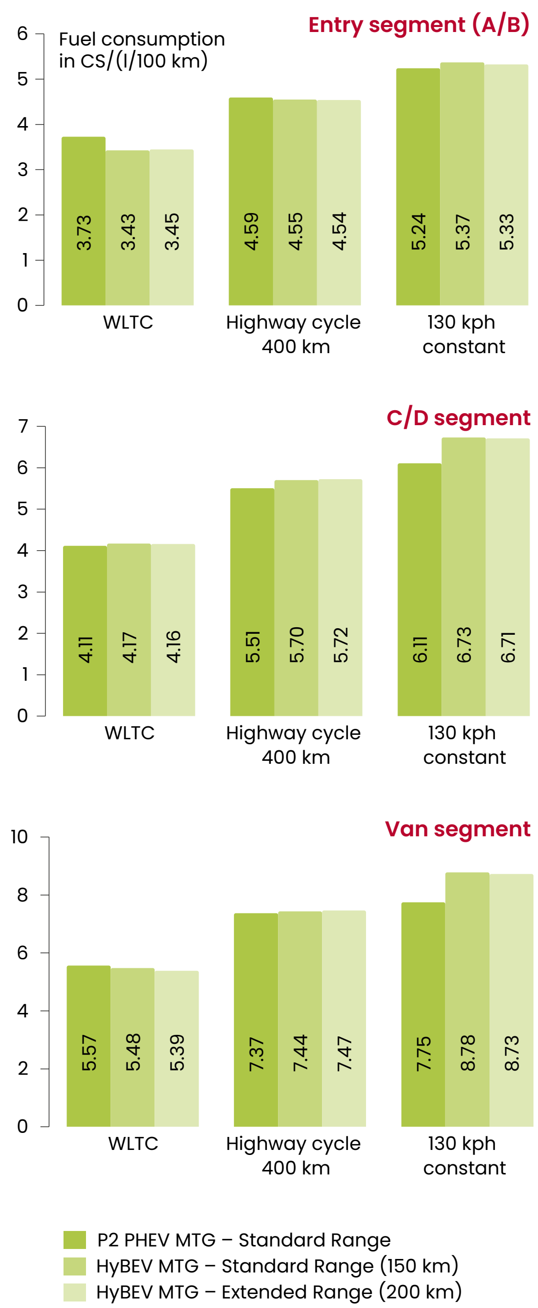
If a combination of BEVs and PHEVs or REEVs is a potential solution, what does an ideal platform strategy and an ideal architecture look like? Looking at traditional plugin hybrid vehicles (PHEV), OEMs have driven the development largely by modifications to existing ICE-based platforms. Hence, the ICE-optimized platform has been a strong and highly limiting boundary condition. Consequently, P2-architectures of parallel hybrids with the engine being the dominant part of the powertrain are considered mainstream today. In this approach, an electrified version of the automatic transmission is used with an integrated e-motor. The battery is typically relegated to confined spaces under the seat, in the transmission tunnel, or under the trunk in an attempt to reach the bare minimum all-electric range required by targeted legislation. The results are often a compromise that ail to excel either as an ICE or electric vehicle. However, another path for hybridization has recently emerged, and offer greater promise by leveraging native BEV platforms. These next generation serial hybrids start with a BEV, and while keeping the BEV architecture dominant, are turned into a HyBEV/REEV, as compared in figure 2.

Compared to traditional hybrids, these HyBEVs/REEVs are characterized by their dominant electric drives and significantly larger batteries. Hence, the range perception as well as the driveability is defined by the BEV-originated characteristics and not by the ICE; even for those models equipped with a large four-cylinder engine as range extender.





2
Traditional PHEV versus HyBEV.



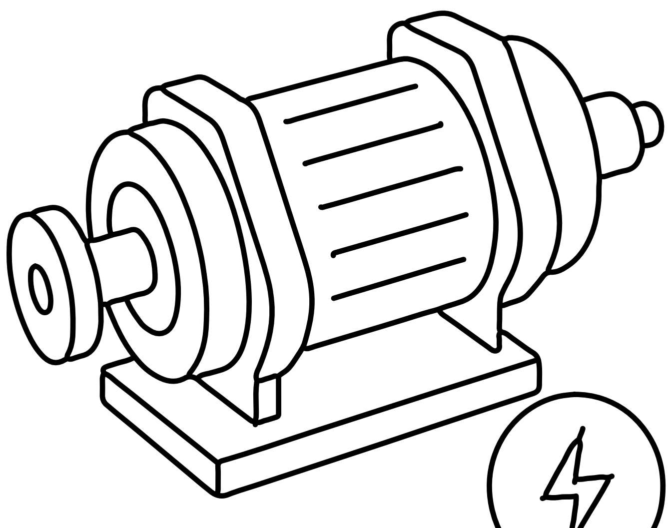
3
Fuel consumption parallel versus serial PHEV.

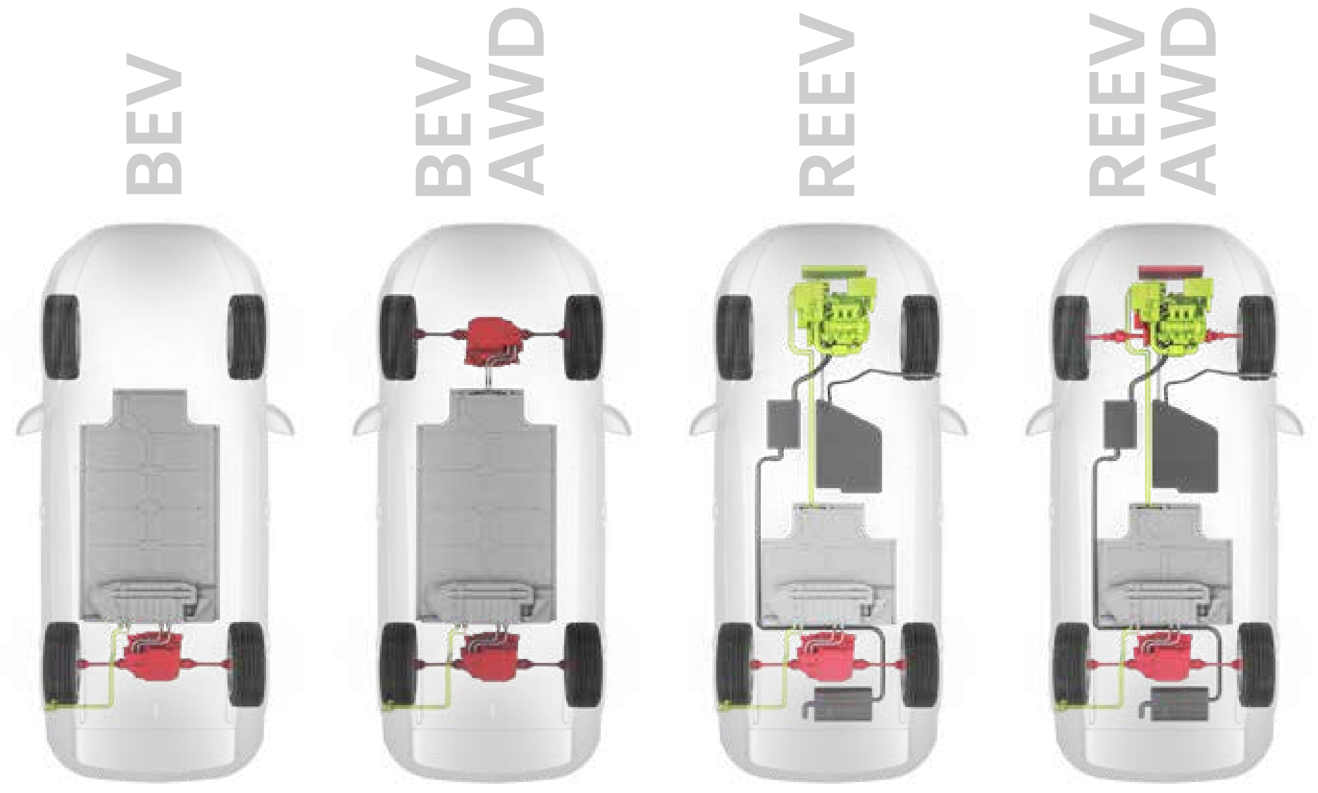
Most of these HyBEV/REEV models originate from Chinese OEMs that started their automotive businesses with BEV-only offerings and therefore have not been constrained by attempts to respect synergies with existing ICE-platforms. Conversely, EU and US OEMs often have developed parallel paths for an ICE-based hybrid platform and a native BEV-only platform.

Besides the described origin of the different approaches, better energy efficiency on long-range trips is sometimes claimed for the P2 architecture. Thus, FEV also compared these two architectures for different vehicle classes (figure 3). Based on the different observed driving scenarios, fuel consumptions rates are comparable. In the A/B segment, HyBEVs/REEVs show slight advantages; while for the van it's the other way around. Only for the artificial sub-scenario "130 kilometers per hour (kph) constant", the P2 parallel hybrid shows a significantly stronger benefit than in other highway cycles. Core assumption for these results are not only high efficiency e-motors and inverters, but also the usage of a dedicated hybrid engine with high thermal efficiency and specific optimal design for each platform.

While fuel consumption results show similar benefits for both architectures, HyBEVs/REEVs offer a strong advantage in packaging and a high degree of commonality in a shared BEV and HyBEV/REEV product platform.

Hence, further usage and optimization of each OEM's existing platform appears to be a reasonable strategy. But wherever a new platform, or how to proceed with Hybrids and BEV in parallel is discussed, a well-designed HyBEV emerges as a "best-of-both-worlds" approach: utilizing established BEV architecture on the one side, and developing highly optimized batteries, e-drives and engines on the other. Only a joint platform for BEVs and HyBEVs/REEVs offers OEMs the flexibility and cost efficiency needed to effectively navigate volatile political boundaries and rapidly changing customer behavior.





4
Architecture steps for common BEV and HyBEV platform.

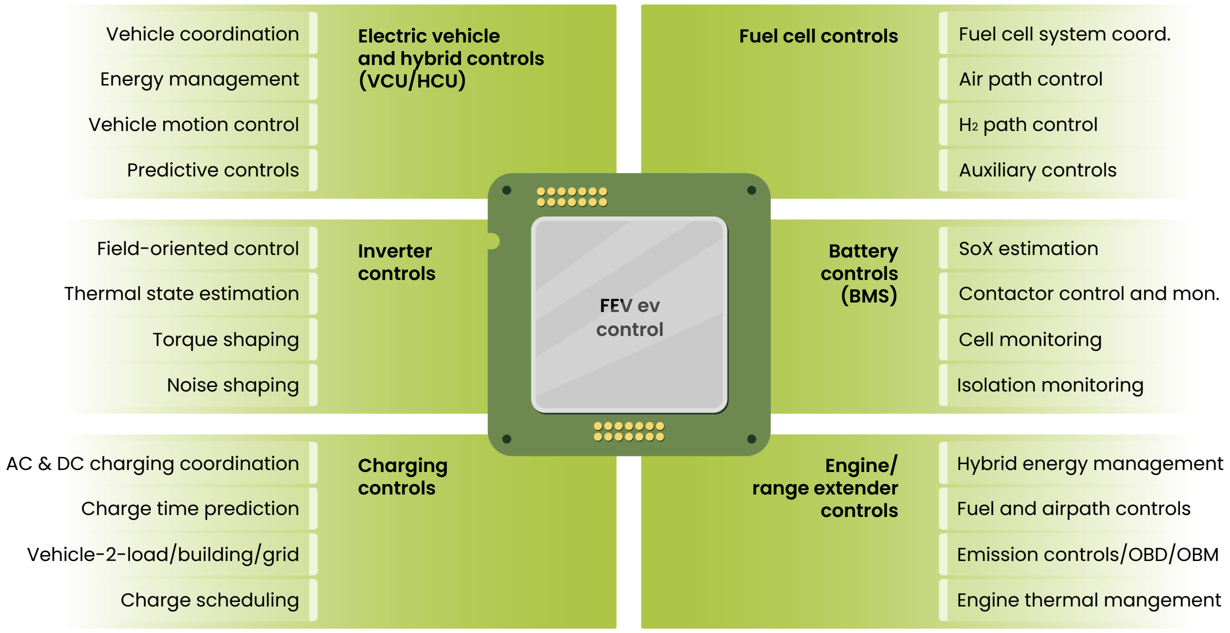
HyBEV/REEV: Platform design and component optimization

Looking at the recommended architectural design, at least for new passenger car platforms, there are some key rules to follow. For BEVs, a system layout with a flatbed underfloor design and one EDU for rear-wheel-drive, or two EDUs for all-wheel-drive, has evolved as a pseudo standard amongst many OEMs. To keep the desired commonality, the RWD-EDU should be carried over, as well as the voltage level, be it 400V or 800V. The charging system can then easily cover both variants, assuming a suitable battery design (see below).

For vehicles, where the RWD-BEV already fulfills all performance requirements, a state-of-the-art four-cylinder engine in the front as pure serial range extender can easily be integrated.

For an all-wheel drive, the engine usually conflicts with the front-EDU in design space. Instead of a modified design space or even a new position for the engine, in this case a substitution of the front-EDU with a multi-mode gearbox allows for optimal mechanical integration of the engine and a front e-drive solution at the same time. With one overall common platform approach, all variants can be realized from pure BEV to range-extended HyBEV; or in the case of sports cars, exciting performance implications may even exist (figure 4). Additionally, the smaller battery size of HyBEVs compared to BEVs helps preserve installation space for exhaust pipes and fuel tanks.

Still, even new platforms can be victims of an OEM's history, and this clean sheet approach may be inhibited because of different brand- or group-specific reasons. However, a holistic approach covering the full view on BEVs and HyBEVs at the same time is mandatory for cost-efficient development and maintenance-friendly production. A scalable, integrated powertrain controls platform can help to further proliferate these benefits.



5
FEV powertrain controls library.

With its experience in integrated development, FEV is ready to support OEMs in making HyBEVs/REEVs a viable part of their portfolio. The company's own vehicle development process and engineering process framework ensures a proper user experience- and requirements-driven view from the beginning and is an enabler to drive suitable decisions on all levels. It can cover full compliance to typical automotive process standards like ASPICE and ISO26262 and can be adopted to be harmonized with the customers' own processes. FEV's integrated simulation tools like the "powertrain design tool" support systematic layout of all propulsion technologies from BEV to all hybrid architectures and even fuel cell applications. This includes right-sizing of the ICE, key electric components, and thermal management subsystems. Additionally, FEV's component databases help to choose the right supplier, with benchmarking support available to aid top-level target setting across any subsystem.

FEV's powertrain controls library provides optimal operating strategies with efficient energy management algorithms for all architectures. These model-based algorithms are typically provided under white-box-model based licenses and can easily be integrated into the customer's own software landscape (figure 5).

Dedicated hybrid component development

While the carry-over of the traction EDU and the charging system has been mentioned above as key boundary conditions, a dedicated REEV-specific design is highly recommended for the other key components. Particularly large BEV-only batteries and dominant ICE in a hybrid architecture are well established technologies, but mostly not ideal for the usage in either "REEV-reshaped" platforms or even full native BEV/REEV-platforms.

The battery usually requires different cell types in order to maintain the voltage level and high discharge C-rates with the reduced energy content. The range extender engines not only have to be optimized for high efficiency in their dedicated operating points, but also with regards to NVH. If the clean platform approach can't be followed, specific design requirements may also need to be considered, leading to a high number of potential range extender designs.

FEV offers multiple customizable approaches and several dedicated REEV batteries as well as dedicated hybrid engines currently under development.

Also, an optimized design of the range-extender generator is highly recommended to account for specific requirements. These include space-constrained integration of the engine and generator, a dedicated bearing concept, the generator and inverter housing, and ideal operating points of the generator to name a few (details about a REEV specific co-development of FEV and DeepDrive can be found on page 28).

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Conclusion

In addition to pure battery electric vehicles, the HyBEVs/REEVs can play a significant role in a path towards climate neutral transportation, bringing together the best of both worlds of ICE/hybrids and BEV. These HyBEVs/REEVs are serial hybrid vehicles with a high all-electric range and are ideally developed based on a joint platform for BEV and HyBEV/REEV. Such a common platform provides the highest flexibility in a volatile market and political environment and offers terrific energy efficiency if properly designed. With its proprietary processes, tools, and in-house IP solutions for hardware and software across all propulsion technologies, FEV offers extensive expertise in holistic powertrain development and dedicated REEV component design.

New brand for innovative engineering and consulting services in a sustainable energy industry

As the world continues to evolve, so does FEV. That's why we are unleashing our technological and strategic expertise from the mobility into the energy sector. The business areas for a sustainable energy environment are wide-ranging and interact with the entire energy value chain. Starting with ecological power generation, through storage and transport, with the most efficient conversion to apply in environmentally friendly devices, products, and systems. There are numerous approaches on our way to a sustainable world. Equally diverse are the individual needs regarding the development, planning, and implementation of specific projects. FEV energy + resources develops and executes tailor-made solutions and concepts to meet these challenges on the way to a sustainable future – from research and consulting to engineering and implementation.

Under the brand FEV energy + resources, holistic solutions for sustainable ecosystems are on offer, including, for example, electrolyzers to produce green hydrogen.

ENERGY + RESOURCES

01

Strategy

Carbon footprint optimization and design for circularity – effective and affordable.

- **Decarbonization pathways**
- **Cost & lifecycle assessment**
- **Regulatory compliance**

02

Technology

360° engineering and industrialization services for energy technology.

- **H_2, CO_2 & derivatives**
- **Heat, electricity grids and storage**
- **Controls and V2X Integration**

03

Project development

Concept design and implementation of integrated ecosystems and green synthetics.

- **Industrial microgrids**
- **Sustainable fuel production**
- **Hydrogen ecosystems**

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FEV energy + resources

#6 Breaking the 30-bar barrier – ***The future of hydrogen-fueled engines***

Due to the high technological maturity of Internal Combustion Engines (ICEs) and the superior gravimetric energy density of hydrogen compared to batteries, interest in hydrogen-powered ICEs is growing as a defossilization solution for on- and off-road applications. These engines typically run as mono-fuel engines on the principle of premixed combustion with spark ignition, which is different from the diffusive combustion of the base diesel setup. Therefore, important decisions must be made in the architecture strategy of combustion engines for operation with hydrogen (figure 1).

The biggest challenge with fuels like hydrogen in achieving performance parity with diesel engines is uncontrolled combustion phenomena (pre-ignition and knocking). Key elements to address this include homogeneity of the air/fuel mixture, turbulence to increase mixing and flame speeds, and avoiding hot zones in the combustion chamber. Cylinder head and port design, boosting system layout, ignition system, and lubrication oil formulation are crucial.

1
Decisions regarding architecture strategy for alternative fuels.

Port fuel injection (PFI) systems have been used in hydrogen engines since 2024. However, direct injection (DI) engines, announced for 2025, address volumetric efficiency loss. These engines require a special charge motion design for sufficient mixture homogenization. A pent roof cylinder head design could improve this but requires a complete redesign.

Maintaining a high degree of commonality with diesel engines and enabling production on the same manufacturing line are key factors in the gradual introduction of hydrogen engines. 3D computational fluid dynamics (CFD) simulations are typically used for layout and optimization, though they can be cost and time intensive.

FEV's charge motion design (CMD) process optimizes head, port, and combustion chamber design for hydrogen combustion, considering multiple fuel-specific factors. It combines CFD simulations, benchmark data, and fuel-specific correlations to rank design variants and provide initial combustion performance impressions. This paper describes the CMD process and its application to evaluate different head concepts for heavy-duty engines, aiming to extend the current limitation to and beyond 30 bar mean effective pressure.

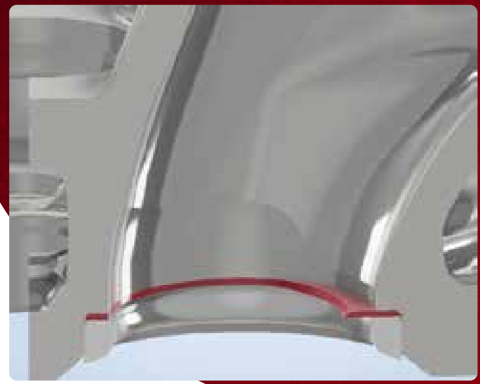
Base engine design

The charge motion design of a commercial diesel engine aims to produce efficient, turbulent airflow for better combustion by controlling swirl and air motion through the combustion chamber. In hydrogen combustion engines, charge motion is influenced by intake port design, piston shape, and injector positioning. Because it is necessary to maintain a high degree of commonality with diesel engines, opportunities to optimize these parameters are limited, and designs such a pent roof cylinder head are often impractical. Other examples include spark-ignition systems and direct injection of gaseous fuels, which traditionally have not been the focus for commercial vehicle engines.

To achieve sufficient tumble charge motion, shrouds can be used to guide incoming air towards the cylinder head, creating tumble-based motion. However, shrouds can reduce volumetric efficiency compared to dedicated tumble-focused port designs, impacting air-fuel ratio and maximum load level.

To address these challenges, FEV has developed a dedicated tumble port and implemented it into a state-of-the-art diesel engine cylinder head. This design maintains a high level of commonality in machining processes, such as valve seat and valve guide cutting (figure 3).

The manufacturing steps for injector and spark plug sleeve installation will need to be individualized for diesel and hydrogen combustion engines. To tackle the challenging task of port design under the given restrictive boundary conditions, FEV used the self-developed charge motion design process, which is described in the following section.

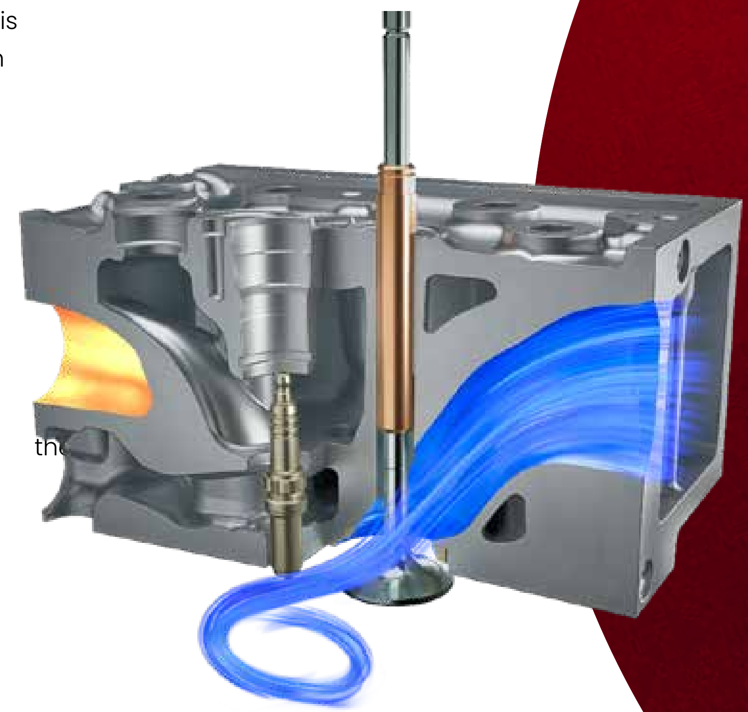


2
FEV's filling port design with tumble shrouds for hydrogen commercial engines.

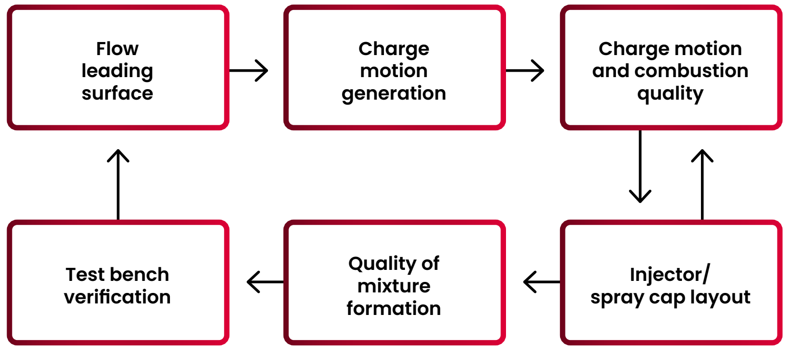
Charge motion design process

The charge motion design process optimizes the flow-guiding surfaces, injector layout, and combustion properties of the system (figure 4) for premixed combustion. This process strongly focuses on in-cylinder 3D-CFD simulations to narrow down and rank the hardware variants to minimize the testing efforts. After running simulations, proprietary scripts analyze in-cylinder flow and turbulence, generating key performance variables. These are then plotted into multiple correlation scatterbands, which consider not only the port and combustion chamber geometry dimensions, but also the charge motion and turbulence parameters. These scatterbands form an essential component of the CMD process and allow for quick evaluation of a given design in relation to benchmarks based on more than four decades of engine development at FEV. Furthermore, the underlying database is used to directly identify required geometry changes.

For premixed combustion systems, a high tumble level is the preferred approach to enable efficient and stable engine operation. The tumble from the inflow is converted into turbulent kinetic energy close to top dead center (TDC), which further supports the mixing process and accelerates flame propagation. Thus, the target of the CMD process is not only to generate a high initial charge motion from the combustion chamber and port layout, but also to ensure the desired tumble motion and conversion into turbulent kinetic energy (TKE).



3
FEV's tumble port design for hydrogen commercial engines.



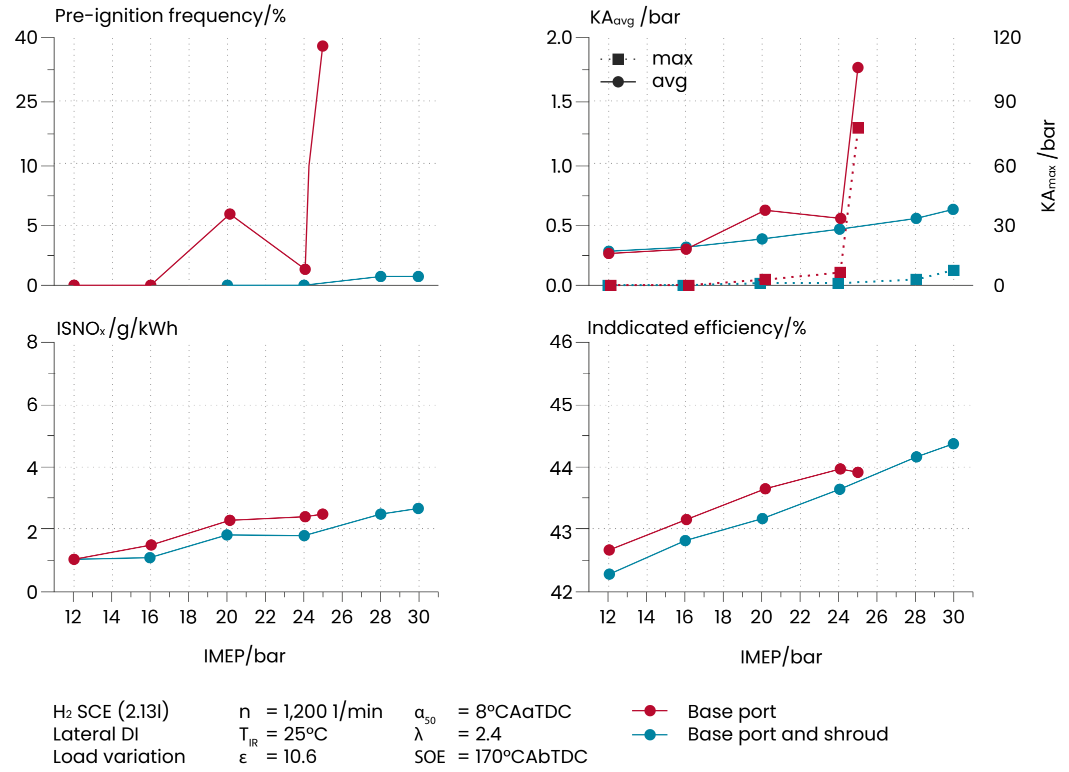
4
FEV's charge motion design process.

Test bench setup and results

For experimental investigations, FEV modified a heavy-duty diesel single-cylinder engine to accept a pre-mixed hydrogen combustion system. A pot bowl piston design achieved a 10.6:1 compression ratio with the flat cylinder head of the base diesel engine. The cylinder head was redesigned for low-pressure direct hydrogen injection in a lateral position, allowing injector swaps without disassembly. To maintain high commonality with the base diesel engine, the valve position was retained. Tumble shrouds were added upstream of the intake valve seats to increase charge motion.

5
Engine characteristics and boundary conditions for operation.

Description	Unit	Value
Bore x stroke	mm	132 x 156
Displacement	cm³	2,135
Compression ratio	–	10.6:1
Coolant/oil temperature	°C	90/90
Temperature in intake runner	°C	25
Injection pressure (DI)	bar	30
Spark plug	–	Cold heat range
Charge motion	–	None/tumble
Injector	–	High flow LPDI



6
Load sweep base port vs tumble shroud, high flow injector, 1200 1/min.

Exhaust backpressure was controlled to match boost pressure. A high-flow low-pressure injector at 30 bar rail pressure was used, and intake air was dried to 3–10% relative humidity.

Avoiding abnormal combustion is critical for achieving high specific power. In DI engines, knock and pre-ignition (PI) are primary concerns. Unlike PFI engines, DI engines do not experience backfire since fuel injection occurs only after intake valves close. Abnormal combustion events depend on the ratio between required ignition energy of the mixture and the energy provided during intake and compression strokes.

Energy supply can be controlled via optimized hardware to minimize oil transport to the combustion chamber and avoid hotspots, and through adapted boundary conditions like lower coolant, oil, and intake temperatures. The required ignition energy of the mixture depends on gas composition, which can be altered by air-fuel ratio (AFR), exhaust gas recirculation (EGR), and water injection. Charge motion is crucial to avoid local rich zones and residual gas pockets, which can cause abnormal combustion.

In the following diagrams, the relevance of charge motion can be observed. At the lower engine speed of 1,200 1/min (figure 6), the tumble configuration (base port and shroud) shows lower PI rates than the base configuration. At 1,600 1/min (figure 7, page 46) the achievable load without tumble increases as the charge motion (generated by the hydrogen injection) gets more intense, and in parallel the cycle duration shortens. Consequently, the time a given volume element is exposed to a hot surface area is reduced and transport speed increases within the combustion chamber.

»Interest in hydrogen-powered ICEs is growing as a decarbonization solution for on- and off-road applications. That is due to the high technological maturity of ICEs and the superior gravimetric energy density of H_2 compared to batteries.«

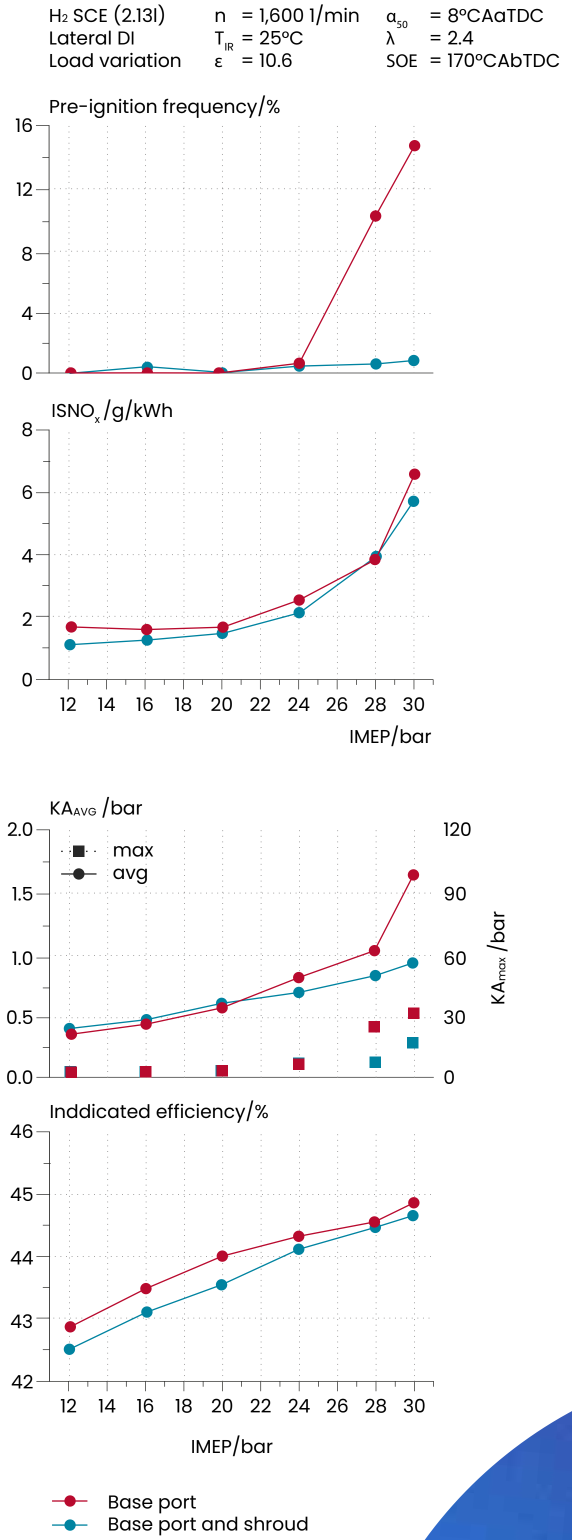
The base configuration also shows significantly more frequent knock with high amplitudes beyond 24 bar Indicated mean effective pressure (IMEP) at 1,200 1/min. The sudden increase in knock shows the challenging operation close to the knock limit for hydrogen engines and the necessity to improve robustness to protect against abnormal combustion. Knock is influenced by mixture homogeneity and peak temperatures during combustion. High PI rates lead to increased combustion chamber temperatures, raising peak pressures and potentially triggering additional knock. This, in turn, causes more pre-ignition, resulting in a self-propelled cycle of abnormal combustion. Charge motion has the same effects for knock as it does for PI, because rich zones are reduced, and increased velocities allow less time for energy transfer.

The improvement in mixture homogeneity causes lower NOx emissions for the tumble setup with similar levels of efficiency. At high PI and knock frequencies, efficiency decreases because combustion occurs before TDC in some cycles, resulting in higher compression and wall heat losses.

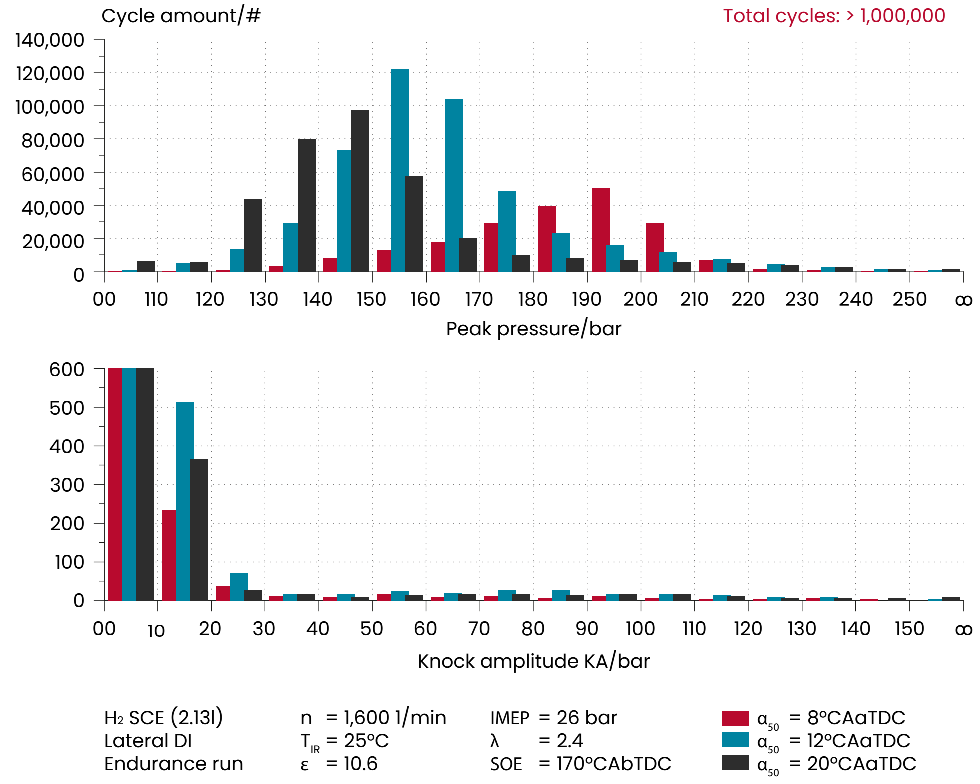
To determine the effect of combustion anomalies on engine health, an endurance run with over 1,000,000 engine cycles was conducted. The engine was operated in high load conditions at rated speed to maximize the strain on the engine. Three different spark timings were investigated, representing a center of combustion of 8°CA, 12°CA, and 20°CA aTDC. The focus was set on the latter two timings to maximize pre-ignition occurrence. The histograms of the peak pressure and knock amplitude are displayed in figure 8.

As expected, the highest average peak pressure happens at the earliest ignition timing, but maximum peak pressures over 230 bar mostly occur at later ignition timings due to pre-ignition. Therefore, the ignition angle needs to be controlled in a way that minimizes excessive stress on the engine. A large number of pre-ignition events resulted in high knock amplitudes even at late ignition angles.

Over 1,700 engine cycles exhibited knock amplitudes above 10 bar while nearly twice as many displayed amplitudes between 5 and 10 bar (not shown in diagram). This excessive strain on the engine did not result in any damage to the cylinder head or piston. Extrapolating the number of pre-ignition events with a PI rate of 0.5% to the engine lifetime (1,200,000 (km) @ 80km/h, 15,000 h, 1% full load) would result in a total number of pre-ignitions of 27,000. This number of pre-ignitions is 16 times higher than tested up to now. However, the next durability run is planned to demonstrate a permissible pre-ignition rate of 0.5% over engine lifetime.



7
Load sweep base port vs shroud, high flow injector, 1,600 1/min.



8
Histogram of peak pressures and knock amplitudes in three operating points over 1,000,000 cycles.

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Conclusion

Introducing tumble motion into the combustion chamber reduces hydrogen dwell time near ignition sources, decreasing pre-ignition and enabling stable operation at 30 bar IMEP. Improved mixture homogeneity, achieved with a high flow injector, enhances engine performance and emissions. Spark timing also influences combustion phenomena; at 40°C intake temperature, combustion centers before 8°CA aTDC cause knock, while late ignition timings increase pre-ignition frequency, narrowing the stable range. An endurance run highlighted critical conditions at late ignition timings with high peak pressures and knock amplitudes.

With optimized hardware, loads beyond 30 bar IMEP are achievable. The next phase of development will focus on CMD-designed cylinder heads, which are expected to further improve mixture formation. Moving forward, efficient charge air cooling and optimized oil formulations will be critical for maximizing the potential of hydrogen-fueled engines in commercial applications.

The content of this article was first published at the International Vienna Motor Symposium 2025.

#7
Fueling the future – Unlocking ***ammonia's potential in high-speed marine applications***

Besides hydrogen, ammonia (NH_3) is the only carbon-free fuel that can be realistically used in an internal combustion engine. Recently, ammonia has been becoming increasingly important as an alternative fuel since it offers a promising opportunity to replace conventional fossil fuels to reduce CO_2 emissions. The liquefaction at a moderate pressure level enables an easier storage in comparison to hydrogen. However, the high toxicity and the associated risk of fatal health hazards requires professional fueling, which is why its use in the road transportation sector is excluded. Therefore, the main focus for a future application is in the marine sector as an additional alternative to green methanol on the path to climate neutrality.

In 2024, FEV extended its test field with a new ammonia infrastructure and developed a comprehensive safety concept for secure test bench operation. Subsequently, thermodynamic investigations on a 2.13 liter single-cylinder engine were conducted. This cylinder displacement is representative of high-speed engines as they are found in propulsion systems of sport fishing boats or as auxiliary units in larger vessels.

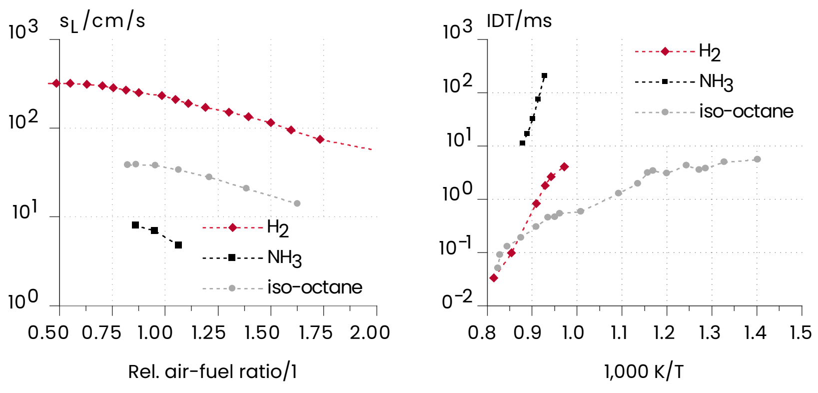
Properties of ammonia and potential combustion process

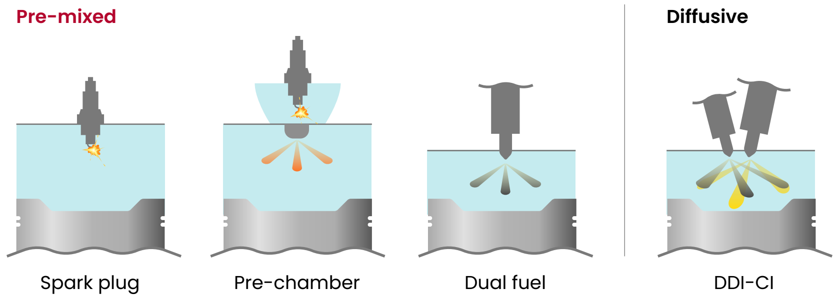
Ammonia is a colorless, pungent-smelling compound of nitrogen and hydrogen. With a lower heating value of 18.6 MJ/kg, its energy density is significantly lower than that of gasoline or diesel. Ammonia can be transported and stored in liquid form at moderate thermodynamic conditions (cooled down to -33°C at 1 bar or compressed to 10 bar at 25°C), similar to liquefied petroleum gas (LPG). In liquid form at 25°C, the density is 0.603 kg/liter, considerably lower than that of conventional fossil fuels. The heat of evaporation at 25°C is 1170 kJ/kg, which is approximately increased by a factor of three compared to gasoline.

In figure 1 the essential combustion parameters of laminar flame speed and auto-ignition delay timings are depicted for various fuels. Here, iso-octane is used as a surrogate for gasoline.

It is evident that the laminar flame speed of NH_3 is lower compared to iso-octane, and far below the values of hydrogen. By contrast, the ignition delay timings which describe the time to initialize an auto-ignition at a certain temperature, are very large for ammonia and require temperatures above 1,000K for an ICE process relevant time scale. Beyond that, the minimal ignition energy of NH_3 is approximately two orders of magnitude higher than that of hydrogen. The combination of the very low laminar flame speed, the high ignition energy, and the large heat of evaporation leads to challenging boundary conditions to ignite ammonia by positive ignition – especially under cold conditions. Therefore, the addition of hydrogen to improve the ignitability and to accelerate the combustion is a subject of current research. On the other hand,

1
Comparison of laminar flame speed (s_L) and ignition delay timings (IDT) of hydrogen, ammonia and iso-octane.





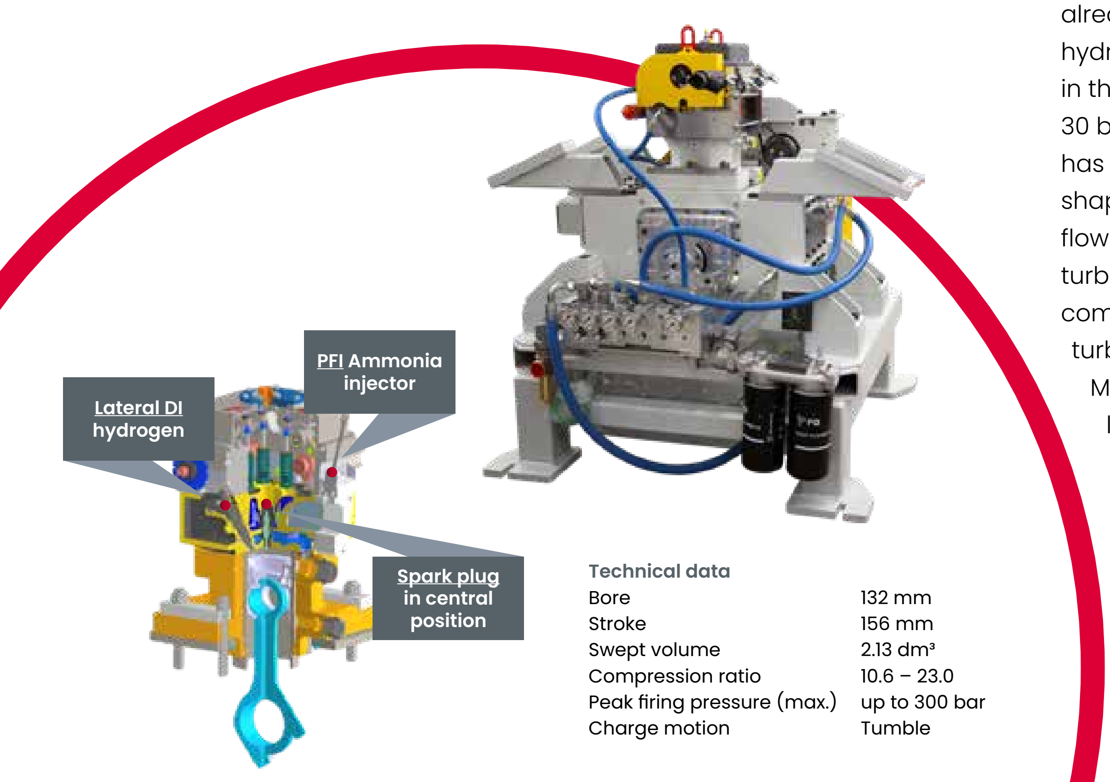
2
Overview of feasible concepts of the combustion process for NH_3.

the very high ignition temperature of 630°C along with the long ignition delay timings represent unfavorable properties for a conventional compression ignition which is in turn beneficial to prevent abnormal combustion phenomena in spark-ignited operation. All things considered, the following combustion processes, as shown in figure 2, are most relevant for ammonia:

In a pre-mixed combustion concept, a positive ignition can be initialized with a spark plug or a pre-chamber whereby engine-specific limits for the bore diameter must be considered to ensure a reasonable spark timing and burn duration. Typically, the threshold for the use of a conventional spark plug lies in a bore diameter range of 130 – 140 mm. Within pre-chamber technology, several variants, such as passive, active, and hydrogen-flushed pre-chambers, are feasible. Another alternative is to inject a small amount of a reactive fuel (such as diesel) directly into the combustion chamber to initialize the combustion of the pre-mixed charge. An additional dual fuel concept is the most promising approach to run a diffusive combustion process in which the heat release of a pilot-injected mass conditions the thermodynamic status of the charge to inject ammonia directly. This so-called dual direct injection compression ignition concept (DDI-CI) is especially relevant for large-bore marine applications and features the highest efficiency potential.

Set-up of a high-speed single cylinder engine

Since the dual fuel concepts are more relevant for large bore engines, the investigations for the high-speed engine class are focusing on spark-ignited combustion with and without a pre-chamber. In Figure 3, the specifications of the test carrier are summarized and the engine set up with NH_3 port fuel injection (gaseous) and optional direct hydrogen injection is depicted. Despite the flat cylinder head design, the intake ports are structurally adapted – supported by FEV's charge motion design process (CMD) – to generate a sufficient level of tumble motion which has already been validated in pure hydrogen operations resulting in the achievement of IMEP = 30 bar. Additionally, the piston has a specially designed bowl shape, and the related squish flow produces additional turbulence at the end of the compression stroke to support turbulent flame speed. Moreover, the centrally located drilling enables the implementation of a conventional J-gap spark plug as well as a passive pre-chamber spark plug.



Technical data

Bore	132 mm
Stroke	156 mm
Swept volume	2.13 dm³
Compression ratio	10.6 – 23.0
Peak firing pressure (max.)	up to 300 bar
Charge motion	Tumble

3
Specifications and set-up of the single-cylinder engine.

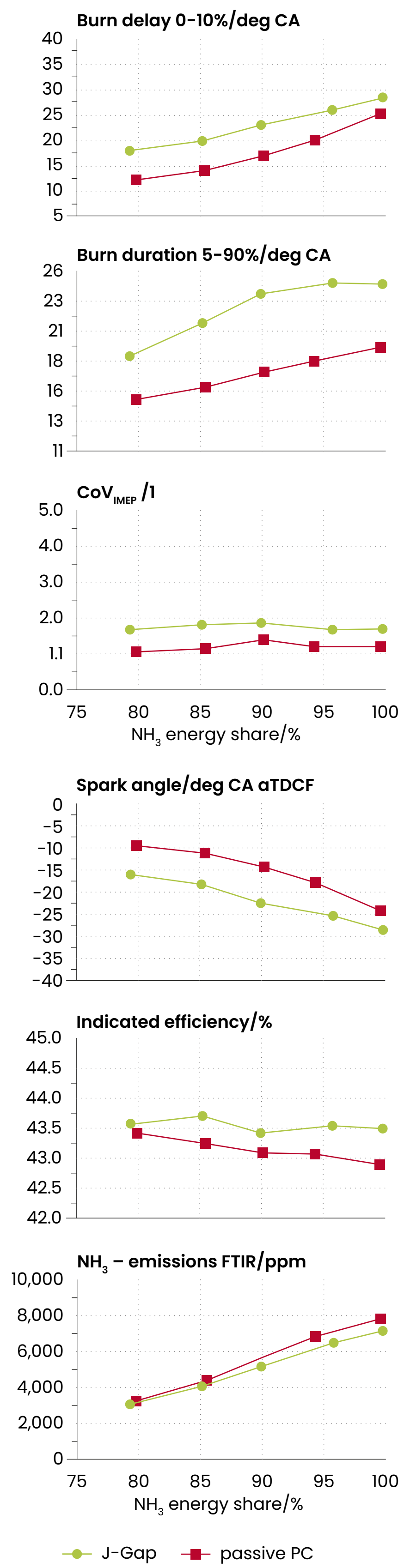
Comparison between J-gap and passive pre-chamber spark plug

The high robustness against abnormal combustion phenomena of ammonia enables basically very high compression ratios in spark ignited operation. However, since the impact of added hydrogen shall be investigated as well, the compression ratio selected is moderate with a value of 15:1. The J-gap spark plug has an electrode gap of 0.7 mm, and the passive pre-chamber is designed with six holes each with 1mm diameter. In figure 4, a variation of the ammonia energy share is depicted for the operating point n = 1,200 1/min and IMEP = 10.6 bar for a stoichiometric air-fuel mixture. The center of combustion is always controlled to an efficiency optimal value of 8°CA after top dead center.

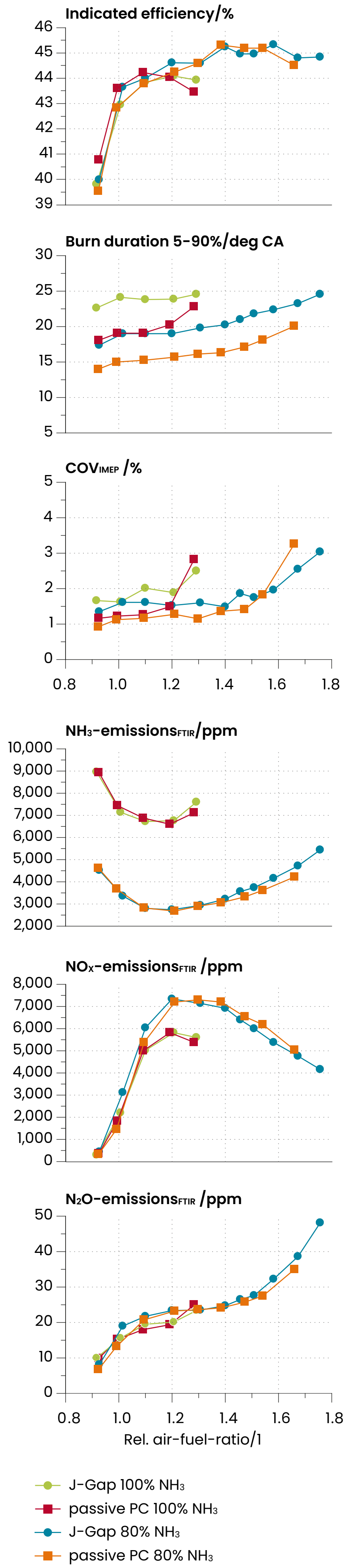
It is evident that the addition of hydrogen significantly accelerates combustion, which is reflected in the shorter values for burn delay and burn duration. The very high flame speed of hydrogen counteracts the characteristics of ammonia. As a matter of principle, the pre-chamber enables a faster combustion due to the large share of simultaneously ignited volume in the main combustion chamber. However, there is no benefit in the indicated efficiency visible since the additional heat losses in the pre-chamber overcompensates the advantage from the faster combustion. The coefficient of variation (COV) describes the combustion stability and is rather independent from the addition of hydrogen. The combustion can be rated as clearly stable, whereby the pre-chamber delivers even better stability. The NH_3 emissions as an indicator for the fuel conversion efficiency correlate with the addition of hydrogen, which is a result of the reduced flame quenching on the walls caused by the small flame thickness of hydrogen.

In relation to pure ammonia (100%) operation, it has to be stated that in FEV's combustion process, the addition of hydrogen is not mandatory with respect to ignitability, combustion stability, and efficiency. Furthermore, the use of a passive pre-chamber is generally recommended to prevent the risk of not being able to reach the optimal center of combustion due to excessive spark advance.

The split of losses as calculated by a three-pressure-analysis are plotted in figure 5, page 52, for the pre-chamber ignition. The results confirm that the addition of hydrogen reduces the losses from non-ideal combustion, but the effects of a higher peak temperature due to faster heat release and the more intensive flame-wall interaction increase the coolant heat losses.



4
Comparison between J-gap and passive pre-chamber ignition in the operating point n = 1,200 1/min, IMEP = 10.6 bar, rel. AFR = 1.0.



Investigation of the influence of hydrogen addition on enleanment

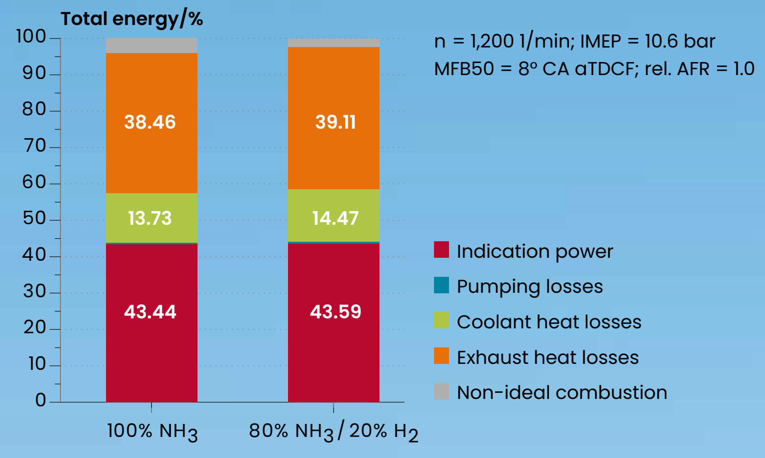
The combustion and emission behavior are directly affected by the relative air-fuel ratio and the presence of hydrogen. In figure 6, there is an air-fuel ratio sweep plotted for both ignition systems and two steps of NH_3 energy share.

As expected, the indicated efficiency is increasing towards lean mixtures and dropping towards enrichment. The burn duration rises with the air-fuel ratio, and the difference between both ignition systems is nearly constant. The investigated range is limited by exceeding the critical level of combustion stability of COV >3%. It is clearly visible that the addition of hydrogen extends the range of stable lean operations significantly while the influence of the ignition system is minor. Regarding emissions, the NH_3 emissions are reduced by a factor of two for 20% hydrogen energy share. In parallel, the NOx emissions show a steep increase up to a plateau in a relative air-fuel range (AFR) of 1.2–1.4. For an efficient operation of the selective catalytic reduction (SCR), a 1:1 ratio between NH_3 and NOx is required. Therefore, moderate lean operations with pure NH_3 might be an auspicious engine operating strategy to combine engine and exhaust after-treatment system efficiency. Besides, the N_2O emissions are increasing with lowered combustion temperatures and correlate with the level of enleanment. Since the global warming potential of N_2O is 273 times higher than the one of CO_2, a dedicated exhaust aftertreatment is mandatory.

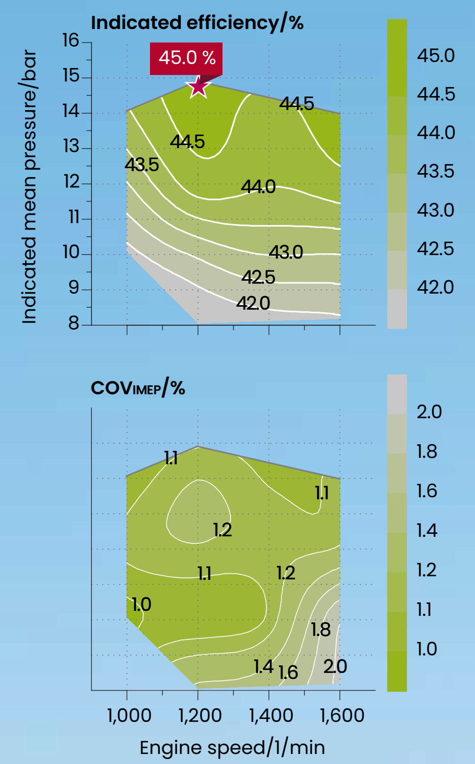
Engine map for 100% NH_3 and pre-chamber ignition

In addition to the detailed analysis in the IMEP = 10.6 bar operating, a wider engine map range has been investigated. The results are depicted in figure 7. A maximum indicated efficiency of 45% could be achieved for IMEP = 15 bar at n = 1,200 1/min. The spark timing is always set for optimal MFB50 position in the entire map with no conflicts with any abnormal combustion phenomena detected. Rather, the IMEP level is restricted by the flow capacity of available injector hardware. Additionally, the combustion stability is plotted in the right-hand map. In a wide range, the COV values are close to 1% while in the high speed and low load area an increase towards 2% can be noted. Overall, the stability is far below any critical values of 3% which demonstrates a very robust and stable combustion process with pure ammonia in combination with the passive pre-chamber.

5
Split of losses for passive pre-chamber ignition with CR = 15.0.



6
Air-fuel ratio sweep for J-gap and passive pre-chamber ignition in the operating point n = 1200 1/min, IMEP = 10.6 bar, MFB50 = 8 deg a TDCF.



7
Engine map for passive pre-chamber ignition and rel. AFR = 1.0.

Conclusion

FEV has demonstrated on a 2.13 liter single-cylinder engine that ammonia is a feasible carbon-free fuel for high-speed marine engines. The tumble supported combustion process is accelerated using a passive pre-chamber spark ignited combustion system whereby the addition of hydrogen as a combustion speed booster can be substituted for stoichiometric and moderate lean conditions. Only for extended lean operation it is necessary to stabilize the combustion with a certain amount of hydrogen, but the increase in NOx and N_2O emissions conflicts with the benefits in engine efficiency and NH_3 emissions. In the investigated operating range, a maximum indicated efficiency of 45% has been achieved with pure ammonia and a stoichiometric mixture. However, slight enleanment – resulting in a much more favorable NH_3-to-NOx ratio for SCR aftertreatment — as well as increasing the compression ratio above 15:1, are promising steps for further optimization toward 50% indicated efficiency.

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#8
Interview with
Dr. Christian Eschmann, Group Director of FEV aerospace

What role does FEV aerospace play within the FEV Group, and what sets you apart from other players in the aviation industry?
Eschmann: The establishment of FEV aerospace demonstrates our clear commitment to aviation and space as a strategic growth area. As a global cross-section topic within the FEV Group, it intertwines with all other business areas. We offer over 45 years of experience across various industry sectors, including automotive, maritime, rail, and energy. Our experts provide a solid foundation for technology transfer. Many methods, tools, and technologies from automotive development – such as hydrogen or battery technology, system integration, and simulation tools – can not only be adapted to aviation applications but set the stage for profound innovations.

This multi-sector expertise is a key strength, allowing us to develop and optimize innovative propulsion solutions tailored for aviation.

»With FEV aerospace, we demonstrate our commitment to advancing sustainable aviation solutions and contributing to the future of carbon-neutral air travel.«

What key innovations are you currently pursuing in aviation?
Eschmann: We focus on sustainable aviation and therefore especially on propulsion technology – an area where FEV has deep expertise. We also see a strong demand for technologies with higher power density. Our innovation priorities include the development and testing of fuel cell and battery systems to enable new aircraft concepts that meet aviation’s stringent safety requirements. Additionally, we are working intensively on the further development of sustainable aviation fuels (SAF) to make existing aircraft operations more sustainable.

What is your long-term vision for sustainable aviation?
Eschmann: The future of aviation will be shaped by a mix of alternative propulsion systems. Depending on the application, this will include battery-electric propulsion, hybrid architectures, hydrogen solutions, and SAF. Short-haul flights will increasingly rely on electric and hybrid systems, while hydrogen will play a relevant role in shorter and medium haul routes. SAF will dominate the long-haul operation.

Besides propulsion, FEV aerospace keeps other aspects in mind, which are crucial for sustainable aviation. These begin on the ground: airports have to transition to a holistic sustainability concept, integrating intelligent energy supply systems for electricity, hydrogen, and SAF. And ground handling will also be carbon-neutral. Furthermore, emission-wise aircraft will not only be net zero regarding CO_2 but also fulfilling low emission noise requirements.

Aircraft designs will also evolve with optimized aerodynamics and innovative structural and cabin concepts, departing from conventional configurations. Additionally, the industry will adopt a holistic sustainability approach throughout the product lifecycle, including material selection and end-of-life recycling.

On top of that, the use of artificial intelligence (AI) will affect the entire aviation industry – from cabin design, through passenger experiences, to automated 4-D flight routing for reduced environmental impact.

FEV aerospace opened an office in the Center of Applied Aeronautical Research (ZAL) in Hamburg, Germany last year.

What challenges currently exist in implementing hydrogen or hybrid propulsion systems for aircraft?

Eschmann: Hydrogen-based propulsion systems face challenges in terms of production capacity, airport infrastructure, refueling, safe onboard storage, and mass. In the field of hybrid propulsion, battery energy density and performance remain key factors. We work on solutions that balance weight, performance, and range to meet aviation's requirements. Especially regarding fuel cell technology, as one of FEV's core competencies, efficiency and thermal management such as innovative cooling concepts are currently in the focus of our engineering activities.

How is FEV aerospace working on the development or optimization of SAF? Are there specific projects or collaborations?

Eschmann: FEV is actively engaged in various SAF-related initiatives, from conceptual development to production methods. Our involvement spans European research projects on fuel characterization, optimization of SAF-compatible engine technologies, and the development of SAF infrastructure at airports, including operator models.

FEV aerospace's partnership with the Hamburg-based Center for Applied Aeronautical Research (ZAL), launched last year, is a key step in this direction. The ZAL TechCenter is a leading hub for aviation innovation, and Hamburg's growing role as a production site for SAF and green hydrogen offer us ideal conditions for industrial collaboration.

Can sustainable aviation fuels (SAF) be a viable solution for aviation in the long term?

Eschmann: SAF will be by far the most important energy source for aviation, particularly for long-haul flights. However, the current challenge lies in scaling up production. Political frameworks, close consultation with industry stakeholders, and economic incentives will be decisive in determining how quickly SAF can be produced in sufficient quantities to meet legal quotas and industry demands. This includes timelines for phasing out conventional fuels and practical, internationally coordinated agreements on new energy sources such as SAF or hydrogen.

Recent delays announced by leading aviation OEMs have highlighted the key issue: technological development must go hand in hand with the advancement of energy infrastructure. Currently, infrastructure development is not keeping pace with industry goals, yet it is essential for the transition to sustainable aviation.

At FEV aerospace, we're committed to bridging that gap – because only by aligning innovation with infrastructure can sustainable aviation truly take off.

FEV aerospace is actively involved as a partner in several key areas:

SAF
Projects on fuel development, production, and integration into existing aircraft

Hydrogen
Fuel cell projects across a range of power classes

Battery-electric
Projects ranging from air taxis to new regional aircraft concepts

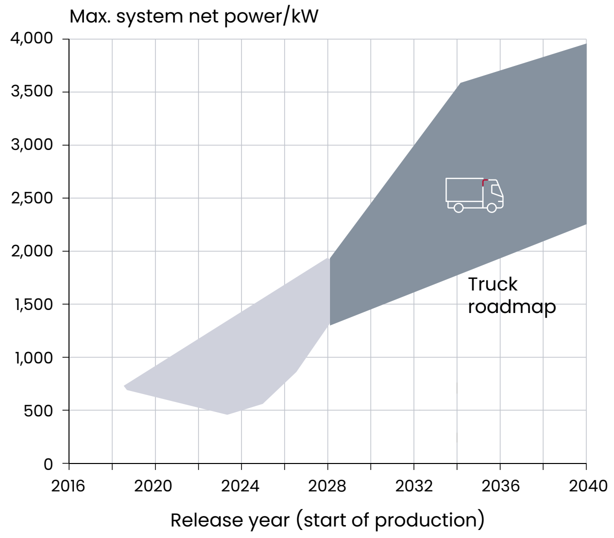
#9 *Powering tomorrow's skies –* Fuel cell propulsion by FEV aerospace

As the aviation industry pushes toward greener propulsion, fuel cell technology is emerging as a key player in the race for sustainable flight. FEV aerospace is at the forefront of this transformation, leveraging decades of expertise to develop high-performance fuel cell solutions tailored for aircraft.

With over 25 years of experience in fuel cell solutions, FEV develops both sub-components and complete fuel cell stacks and systems in-house. Through FEV aerospace, the company integrates its expertise in ground-based propulsion with aviation requirements, driving the development of sustainable and safe aircraft propulsion.

A key challenge for fuel cell adoption in aviation is increasing stack power density. To address this, FEV is developing aviation-optimized bipolar plate materials along with intelligent control strategies.

As part of its benchmarking efforts, FEV generates scatterband diagrams that help customers assess their products against competitors. Analyses show a significant rise in maximum fuel cell system power in recent years. By combining these insights with customer discussions and market trend evaluations, FEV forecasts future performance targets. For example, in the heavy-duty truck segment, projections indicate that system performance must increase substantially by the mid-2030s to meet industry and regulatory expectations.



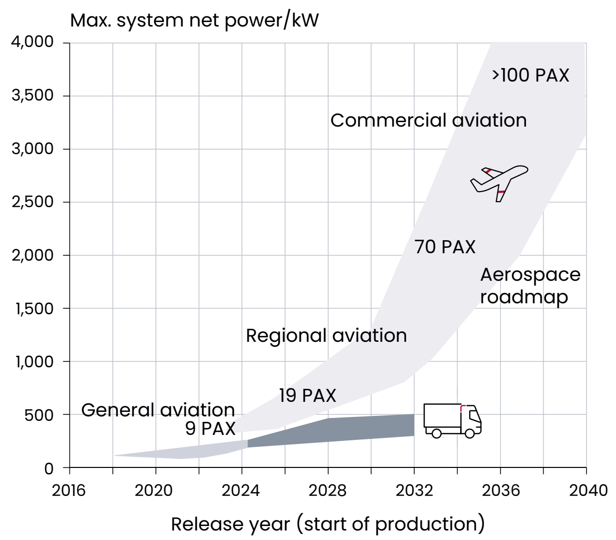
1
FEV's scatterband analysis illustrating the evolution of fuel cell system performance in heavy-duty trucks and projected targets for future development.

»With over 25 years of experience in fuel cell solutions, FEV develops both sub-components as well as complete fuel cell stacks and systems in-house.«

For the aviation sector, forecasts indicate that fuel cell system power must increase significantly to meet regional and commercial aviation demands. To power a nine-passenger (PAX) aircraft, today's ground-based system power would need to double. Fortunately, an eightfold performance increase is projected by 2040, suitable for aircraft exceeding 100 PAX.

In addition to increasing system power, the mass of fuel cell systems needs to be significantly reduced. A key reason why fuel cells cannot compete with the power density of jet engines is the way they are cooled. In jet engines (as well as in piston engines), much of the heat loss is dissipated through the exhaust. Fuel cells produce less waste heat for the same power output due to their higher efficiency, but this has to be dissipated almost entirely through the coolant at a much lower temperature level. This requires a more complex and larger cooling system, which not only increases the mass of the system but also potentially the drag of the aircraft.

Another challenge becomes apparent when considering the operation of a fuel cell at different operating points. When a fuel cell is operating at high power, the cell voltages and therefore the efficiency of the cells are lower than when operating at low power. This characteristic has a significant impact on the use of fuel cells in aircraft. In order to keep the cooling system as small and light as possible, and thus minimize the drag caused by the radiator surfaces, the amount of waste heat should be as low as



2
Forecast of fuel cell system power requirements for regional and commercial aircraft, highlighting the necessary advancements to support larger passenger capacities by 2040.

possible. This can only be achieved by operating the cells at the lowest possible load point, (i.e. at the highest possible cell voltage). To ensure that the fuel cell system can still provide the required propulsion power for the aircraft, fuel cell stacks for aeronautical applications must be significantly oversized. However, larger fuel cell stacks and systems also increase their mass. The correct design of the propulsion and cooling system is therefore a compromise between the mass and drag of the cooling system and the mass of the fuel cell system and stack.

FEV uses its extensive experience and model library to optimize this trade-off for its customers. In addition, intelligent control concepts developed by the company enable further weight savings. Particularly during short acceleration and start-up phases, it makes sense to leave the operating point of optimum efficiency and operate the fuel cell system at higher power. The higher heat dissipation associated with this can be achieved using customized control strategies without damaging the cells. FEV offers its customers intelligent concepts tailored to the specific application.

A key strategy for increasing power density and reducing propulsion mass is optimizing fuel cell stacks. In the BiFoil-Stack research project, funded by the BMWi (German Federal Ministry for Economic Affairs), a high-power fuel cell stack is being developed to maximize power density and efficiency – ideal for aircraft applications.

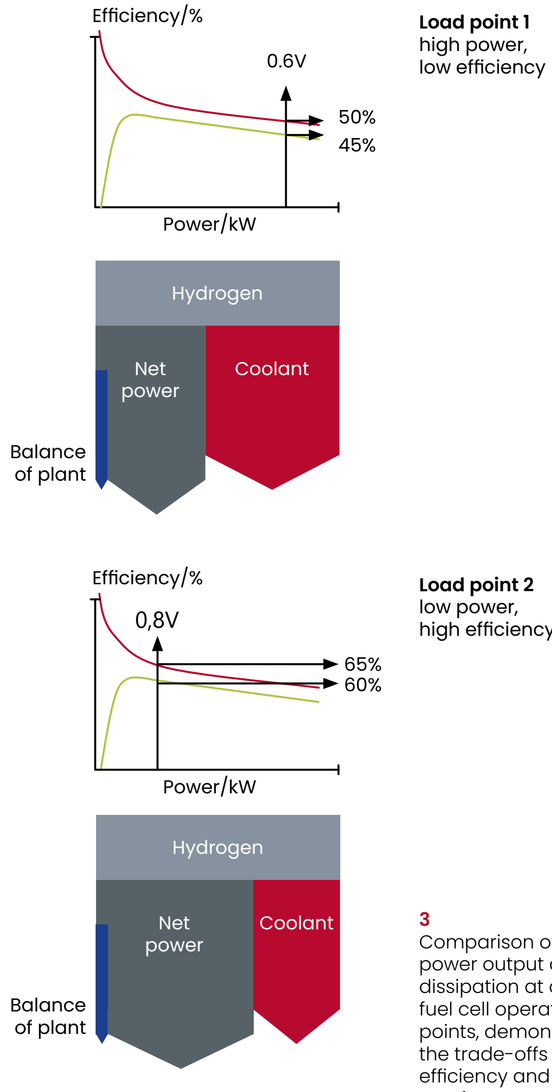
To further enhance performance, traditional stainless steel or titanium bipolar plates are being replaced with an innovative foil-based graphite composite material in collaboration with the Fraunhofer Institute UMSICHT. This material combines the strengths of both metal and graphite bipolar plates: exceptional corrosion resistance for long service life with minimal degradation and significantly reduced weight. Unlike conventional composite graphite plates, these bipolar plates are stamped from thin foils and welded, similar to metal plates, rather than being injection molded.

This advanced manufacturing process not only reduces weight but also lowers production costs and increases throughput compared to conventional graphite bipolar plates, making high-efficiency fuel cell stacks more viable for aerospace applications.

FEV's scatterband analysis highlights the significant weight savings enabled by the innovative foil-based material. At the same operating point, foil-based graphite compound bipolar plates achieve approximately 20% higher specific power density than stainless steel plates and 35% higher than conventional graphite-based plates. Only titanium bipolar plates offer greater power density, but their prohibitive cost makes them less viable.

FEV's compound foil-based bipolar plate concept bridges this gap, delivering high power densities at a fraction of the cost, making it a strong candidate for aerospace applications.

By integrating ultra-lightweight fuel cell stacks, optimized system layouts, and application-specific control strategies, FEV Aerospace empowers its customers to develop next-generation fuel cell propulsion systems for aviation.



3
Comparison of net power output and heat dissipation at different fuel cell operating points, demonstrating the trade-offs in efficiency and cooling requirements.

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»SAF is the most effective measure for achieving net-zero aviation, with the potential to reduce climate-impacting emissions by over 90%.«

#10 *Beyond fossil fuels* – How SAF and system thinking will defossilize aviation

The global transport sector is a major contributor to greenhouse gas emissions and plays a crucial role in achieving climate neutrality by 2050. To reach this target, different technologies are required across various transport modes. In road transport, battery electric and plug-in hybrid vehicles are expected to dominate. The maritime sector will use energy carriers like ammonia, methanol, Fischer-Tropsch fuels, LNG/CNG, and hydrogen. Depending on energy density, safety, storage, and infrastructure, all will likely play a role in future shipping. In the case of aviation, the industry requires tailored solutions that are largely dependent on flight range. For short-range flights, battery-electric propulsion and hydrogen-based technologies are emerging as viable alternatives. Advances in battery energy density and hydrogen fuel cell technology could make these options competitive for regional and domestic flights. For long-range, intercontinental flights, sustainable aviation fuels (SAFs) will play a critical role. These fuels, derived from biomass, waste, or synthetic processes, can be used in existing aircraft engines and infrastructure, significantly reducing the carbon footprint of long-haul flights.

International efforts for climate-relevant emission reduction in aviation

Given the aviation industry's complexity and international nature, coordinated global action is essential to reduce emissions. Several key initiatives are driving this transition.

The International Civil Aviation Organization (ICAO) aims for net-zero CO_2 emissions by 2050 through aircraft efficiency (2% annual fuel efficiency improvement), SAF, operational improvements, and carbon offsetting. To facilitate this development, the ICAO created CORSIA (Carbon Offsetting and Reduction Scheme for International Aviation). It is a market-based system that requires airlines to reduce emissions exceeding 2019 levels by either using SAF or carbon offsetting. CORSIA is currently in a voluntary test phase but will be mandatory for all international aircraft operators by 2027.

The EU mandates increasing SAF use through ReFuelEU Aviation, requiring 20% SAF by 2035 (with a sub-target of 5% renewable fuels of non-biological orgin (RFNBO)), rising to 70% by 2050 (35% RFNBO). The EU Emission Trading System (ETS) will be covering flights within the European Economic Area, with an option to also cover flights leaving or entering the EEA after 2026, if the CORSIA system proves to be ineffective.

Alongside these global and regional initiatives, national strategies also play a role, such as the U.S.'s SAF Grand Challenge, which aims to scale up SAF production. Similarly, UK's Jet Zero Strategy promotes low-emissions aircraft, and Germany's National Hydrogen Strategy supports SAF and hydrogen in aviation. In addition to governmental targets, there are also commitments from the aviation industry itself. Organizations like the International Air Transport Association (IATA), as well as individual airlines, are investing in SAFs, hydrogen, and other efficiency improvements.

SAF is the most effective measure for achieving net-zero aviation, with the potential to reduce climate-impacting emissions by over 90%. Efficiency enhancements from air traffic optimization, aircraft design, and engine design, are expected to contribute as much as 15-25%. In combination with carbon offsetting, an overall climate neutral air traffic can be achieved.

Sustainable aviation fuel (SAF) pathways and commercial readiness

In contrast to fuels used in other forms of transportation, the properties of aviation fuels are regulated extremely precisely worldwide. These properties are dictated by aviation standards such as ASTM D1655 (for conventional Jet A/A-1) and ASTM D7566 (for SAF). The main reasons for this are safety concerns, and weight and volume restrictions. For example, where a minimum energy density of 43 MJ/kg is prescribed, the alcohol content is limited to 0.5% due to the reduced energy density and possible corrosive effects,. The viscosity must also be sufficiently low even at low temperatures to remain pumpable, with the freezing point set at a minimum of -47°C for high altitude operation. Because aromatics cause elastomers to swell and influence the performance of reinforcement seals, the aromatic content must be controlled within the range of 5–25%. These are just a few of many considerations.

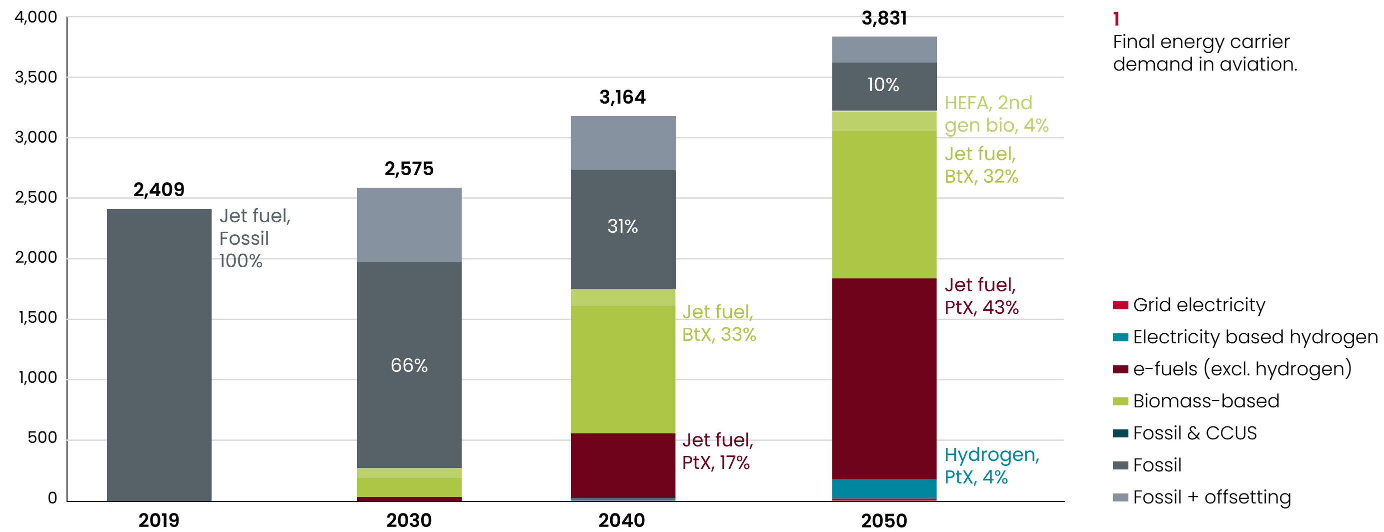
Regardless of these factors, achieving climate-neutral aviation requires large-scale deployment of SAF. Several production pathways have been developed, with different technological approaches and levels of commercial maturity. However, approval under ASTM D7566 and commercial availability vary significantly. The most relevant SAF pathways include biomass-based Hydroprocessed Esters and Fatty Acids (HEFA), Alcohol-to-Jet (AtJ), Fischer-Tropsch (FT), Methanol-to-Kerosene (MtK); although MtK, AtJ and FT can also be obtained via Power-to-Liquid (PtL/PtX) processes that use renewable hydrogen and captured CO_2 to synthesize jet fuel. Several PtX projects are underway, including Atmosfair, Norsk e-Fuel, and Synhelion, but large-scale production is still in its early stages.

The HEFA process, which converts waste oils, fats, and plant-based lipids into paraffinic jet fuel through hydrogenation, is currently the most commercially viable SAF pathway. HEFA-derived fuels are ASTM-certified and can be blended up to 50% with conventional jet fuel. Several commercial-scale production facilities are operational, including those operated by Neste, World Energy, and TotalEnergies.

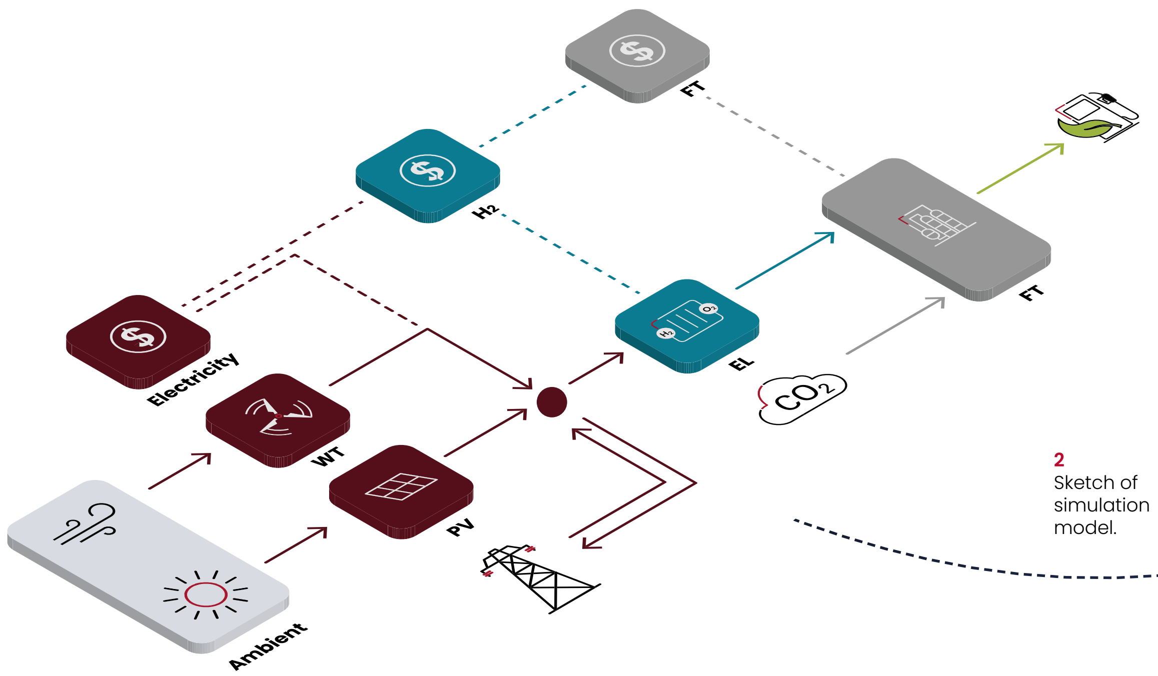
AtJ involves converting bio-based ethanol or butanol into jet fuel through dehydration, oligomerization, and hydrogenation. Here to the ASTM-certification allows blending up to 50%, but commercial production remains limited. FT synthesis, which utilizes synthesis gas ($CO + H_2$) from biomass, waste, or other carbon sources and to produce synthetic hydrocarbons, is another ASTM-approved pathway (again up to 50% blend). While FT has been commercially applied in other sectors, SAF production at scale remains constrained, with only a few projects aiming for large-scale implementation.

The MtK pathway for producing SAF is currently undergoing evaluation for ASTM certification. In early 2023, ExxonMobil submitted more than 100 gallons of MtK-derived fuel for assessment under the ASTM D4054 process. The timeline for full ASTM approval remains uncertain as it depends on the outcomes of these evaluations, but several pilot projects are in development to advance MtK technology. MissionGreenFuels focuses on developing a strategy for ASTM certification, aiming to expedite market readiness.

In the coming decades, all these fuel types and carbon offsetting will likely be used (figure 1) to varying degrees. Initially, carbon offsetting will be a very cost attractive alternative to SAF and is expected to be the main lever to reduce carbon emissions for international aviation in the EU through 2030. However, by 2040 significant shares of SAF, mainly from biogenic sources, will need to be available on the market to be compliant with EU legislation. By the middle of this century, increasing amounts of electricity-based SAF will be required, as biomass feedstock availability is likely to reach its limits by then. Hydrogen will likely only play a minor role, mainly for short- and maybe medium-haul flights.



1
Final energy carrier demand in aviation.



2
Sketch of simulation model.

	Fully centralized		Partly centralized		Fully distributed	
	Short-term	Long-term	Short-term	Long-term	Short-term	Long-term
USA	>200	~140	>230	<150	>320	>250
EU	>220	~150	~250€	~160	~300	~250
MENA	>220	~150	>220	~150	>220	<200

High attractivity · Moderate attractivity · Low attractivity

3
Techno-economic simulation results for short-term (2030) and long-term (2050) SAF production in centralized versus decentralized production in different regions of the world.

Challenges in the implementation and commercialization of SAF
SAF face challenges in production, cost, infrastructure, and regulation. Currently, SAF accounts for less than 0.1% of global jet fuel use, with HEFA fuels relying on scarce waste oils and fats. Advanced alternatives like FT and PtL require scaling; while others such as MtK lack certification, delaying commercialization.

Regulatory hurdles also slow down market entry. While HEFA and FT fuels meet ASTM standards, newer pathways still await approval. Inconsistent policies across regions add to market uncertainty, discouraging long-term investment. Airlines struggle with voluntary SAF adoption, and while some sign long-term agreements, overall demand remains too low to drive large-scale expansion, which influences another key obstacle – cost. Because SAF is significantly more expensive to produce than conventional jet fuel, without strong policy incentives, airlines have little economic motivation for large scale adoption.

Cost projections for SAF production in 2030 and 2050

To understand the future development of the SAF market, and with that, the defossilization of aviation, it is imperative to have more detailed insights into the specific characteristics of SAF production and its associated costs.

To gain these insights, FEV developed a techno-economic simulation model to analyze the feasibility, efficiency, and costs of a renewable electricity-based FT kerosene production under varying input parameters. The model incorporates different power sources (grid electricity, renewables), CO_2 feedstock sources (industrial capture, DAC, biogenic), plant sizes, and geographical locations. Additionally, it assesses the impact of CO_2 logistics and SAF transport on overall system performance.

The model was also used to estimate the levelized cost of SAF production by 2030 (short-term) and 2050 (long-term) under different plant configurations (fully centralized, partly centralized, fully distributed) and regions, alongside changing boundary conditions (e.g. levelized cost of renewable electricity and solar/wind power ratio, CO_2 availability, infrastructure and distance to the end-user, technology scalability, necessity of H2 transport, etc.). The sample results below have been obtained under very specific constraints, such as the location of the plants for fully centralized, partly centralized, and fully distributed operation. The specific figures are therefore only valid for these locations, but the general statements are broadly applicable.

The results indicate significant cost variations based on production scale and regional conditions, highlighting that centralized production remains the most cost-effective approach, while distributed production may require stronger policy support and cost reductions to become viable at scale.

Fully centralized SAF production achieves the lowest costs, with long-term estimates of ~140–150 €/MWh across all regions, as the economies of scale of a larger plant outweigh the higher transportation costs of the educts and products. Partly centralized configurations result in moderately higher costs, ranging from ~150 €/MWh (MENA) to ~160 €/MWh (EU).

Fully distributed production leads to the highest costs, exceeding 300 €/MWh in the short term and settling at >250 €/MWh in the long term, particularly in the EU and USA as location limitations are likely to reduce solar and/or wind output drastically. Only the MENA region is highly attractive for distributed production, as even with location limitations, good solar and wind outputs keep the price below 200 €/MWh.

The results suggest a significant reduction in SAF production costs by 2050, driven by CAPEX reductions and efficiency improvements across key technologies. Centralized plants are expected to benefit the most due to economies of scale, as larger facilities will further optimize production costs. With optimized plant layouts and locations, even cost levels as low as 100 €/MWh might be achievable in a best-case scenario when considering costs of electricity, assumed capacity factors, and CO_2 sourcing costs. In Europe, however, plant sizes might be constrained by land availability, particularly for renewable energy installations like PV panels. As a result, partly centralized configurations may emerge as a long-term viable alternative.

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FEV's SAF services

This is just one of the many puzzle pieces needed to understand the future of SAF as part of the solution for a carbon-neutral aviation industry. By combining the competencies of FEV aerospace and FEV energy + resources, the engineering service provider delivers end-to-end solutions in the field of sustainable fuels and SAF. To bring green fuel plants to life jointly with its partners, FEV services span three key areas:

Market and technical intelligence and due diligence – This includes techno-economic modeling, demand forecasting, regulatory analysis, and supply chain evaluation, ensuring a solid foundation for project viability.

Project development – FEV facilitates consortium building, establishes partnerships and contractual agreements, secures private and public funding, and manages PMO and certification processes to advance projects from concept to execution.

Engineering and implementation – FEV's services cover feedstock analysis and production concept development, technical design and simulation, feasibility studies, and FEED engineering up to FID and implementation in collaboration with selected EPC partners to ensure seamless project execution.

Signature solutions

ONLY AT FEV!

#11 SPECTRUM regularly presents a selection of these unique solutions from FEV

Find further FEV Signature solutions here:

FEV fuel cell aging models

Hydrogen fuel cells are a key technology for carbon-neutral mobility, but maximizing their lifetime duty cycle under real-world conditions remains a major engineering challenge. FEV's advanced fuel cell aging models offer OEMs and suppliers a powerful solution to analyze, predict, and improve the durability of fuel cell stacks in mobile applications.

The model combines physical equations with empirical correlations to capture key aging mechanisms while enabling fast-running models. These physically based models use operating conditions such as temperature, pressure, humidity, and current load as inputs. FEV's modular simulation models account for the most important aging mechanisms, such as membrane aging, catalyst aging, GDL aging and bipolar plate aging. Both degradation processes, reversible and irreversible aging, are captured, which is important to match real measurement data and define operating strategies including recovery.

From simulation to real-world validation

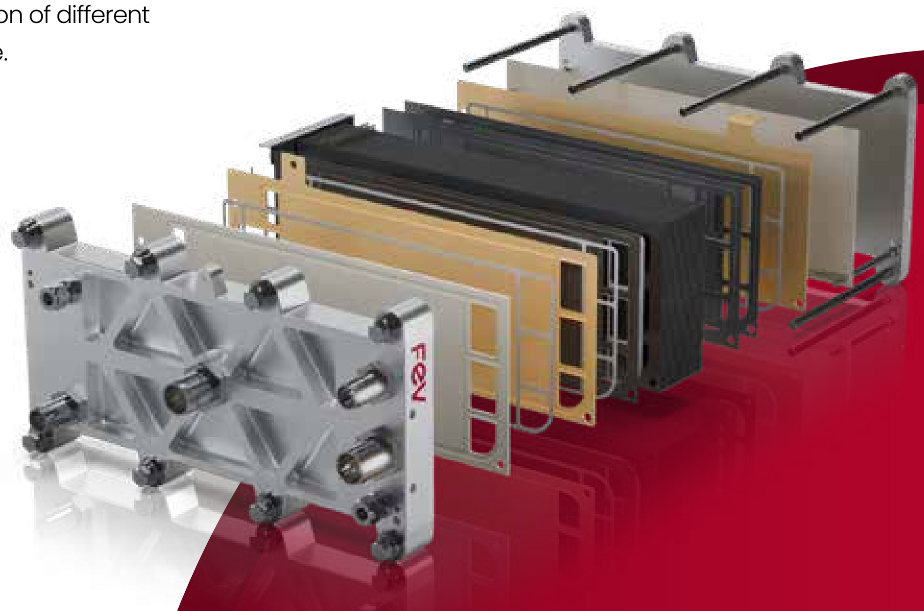
FEV supports customers to quantify the end-of-life behavior, improve operating strategies, and reduce development time by constructing tailored accelerated durability tests. This is important because fuel cell aging is highly dependent on specific use cases whereas fuel cell stack manufacturers often employ their own unique durability cycles. FEV aging models transfer these reference cycles into application-specific aging behavior and enable a comparison of different fuel cell suppliers and hardware.

FEV has successfully used these models within various projects for different customers and applications. In a recent project with a leading commercial vehicle manufacturer, FEV applied the degradation model and defined an accelerated durability test cycle. The results were meaningful lifetime forecasts and radically reduced development time – by a factor greater than six.

Flexible integration and customer-oriented approach

FEV's white-box philosophy empowers customers to adapt the models for their own testing environments and simulation frameworks. Whether integrated into existing control strategies, or used as part of FEV's validation services, the aging models are designed to be flexible, transparent, and easy to calibrate.

With its fuel cell expertise and deep understanding of aging mechanisms, FEV delivers validated tools that support long-term performance, reduce development costs and enable the next generation of efficient hydrogen-powered mobility.



Predictive gear shifting software

FEV's predictive gear shifting software enables an intelligent, forward-looking control of the drivetrain-based on road previews and is optimized in real time. The ADAS-based solution processes eHorizon data such as slope, curvature, and traffic signs to determine the optimal shifting strategy for each driving situation.

Whether driven manually or via cruise control, the software continuously calculates the most energy-efficient gear – even anticipating when to avoid or initiate eco roll phases. The result: improved energy efficiency, smoother driving, and reduced CO_2 emissions in both passenger and commercial vehicles.

Thanks to a low processor load and modular structure, the software is easy to integrate into existing ECUs and is adaptable for a wide range of applications, from predictive speed control to range optimization.

Proven performance, tailored to customer's needs

FEV's predictive software is already in use in series development and has been tested extensively under real-world conditions. Its white-box architecture enables OEMs and suppliers to further adapt the system to their needs – or rely on FEV for turnkey calibration and validation, from MiL and HiL to on-road durability testing.

In this solution, FEV combines deep system expertise with intelligent software to create real-world efficiency for today and tomorrow.

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