FEV

#76

SPECTRUM

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Dear reader,

in this issue, CEO Stefan Pischinger talks to SPECTRUM about the first rebranding that FEV has implemented for the first time since its founding 45 years ago. Part of this rebranding is the new logo. But it also goes hand in hand with the new look of this customer magazine. In addition, in this issue we provide insights into efficiency improvements and greater practicality of locally emission-free mobile machinery and equipment, using the example of a concrete trowel. This is a relevant topic, as more and more cities are announcing stipulations that such helpers will no longer be allowed to emit any emissions in the coming years.

Fuel cells are considered as a key driver of the energy transition. In this context, bipolar plates in particular are an important component for improvements in terms of manufacturability and durability. On the following pages, we highlight solutions that take advantage of positive material properties and further improve performance and power density. In another article, we address electric vehicles that use permanent magnet excited electric traction machines. They rely on raw materials such as rare earths, which are considered critical in terms of a sustainable circular economy and their geopolitical development. We highlight ways to address these challenges.

Another development challenge for e-vehicles is the driving range required by the market and the correspondingly required energy density in the battery cells. FEV is working on technologies that are able to realize these required energy densities while maintaining or increasing safety and power density. Solid-state batteries offer the potential to realize the increasing ranges of battery electric vehicles expected by the end of the decade. We give you an exclusive look into our work on the topic in an article.

We also look at the opportunity for software-defined vehicles to unlock new revenue potential and highlight key success factors. And in the context of Euro 7 legislation, this issue is dedicated to FEV's holistic approach to meeting the new stricter requirements.

I wish you an interesting read with exciting impressions true to our philosophy "Feel EVolution"!

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

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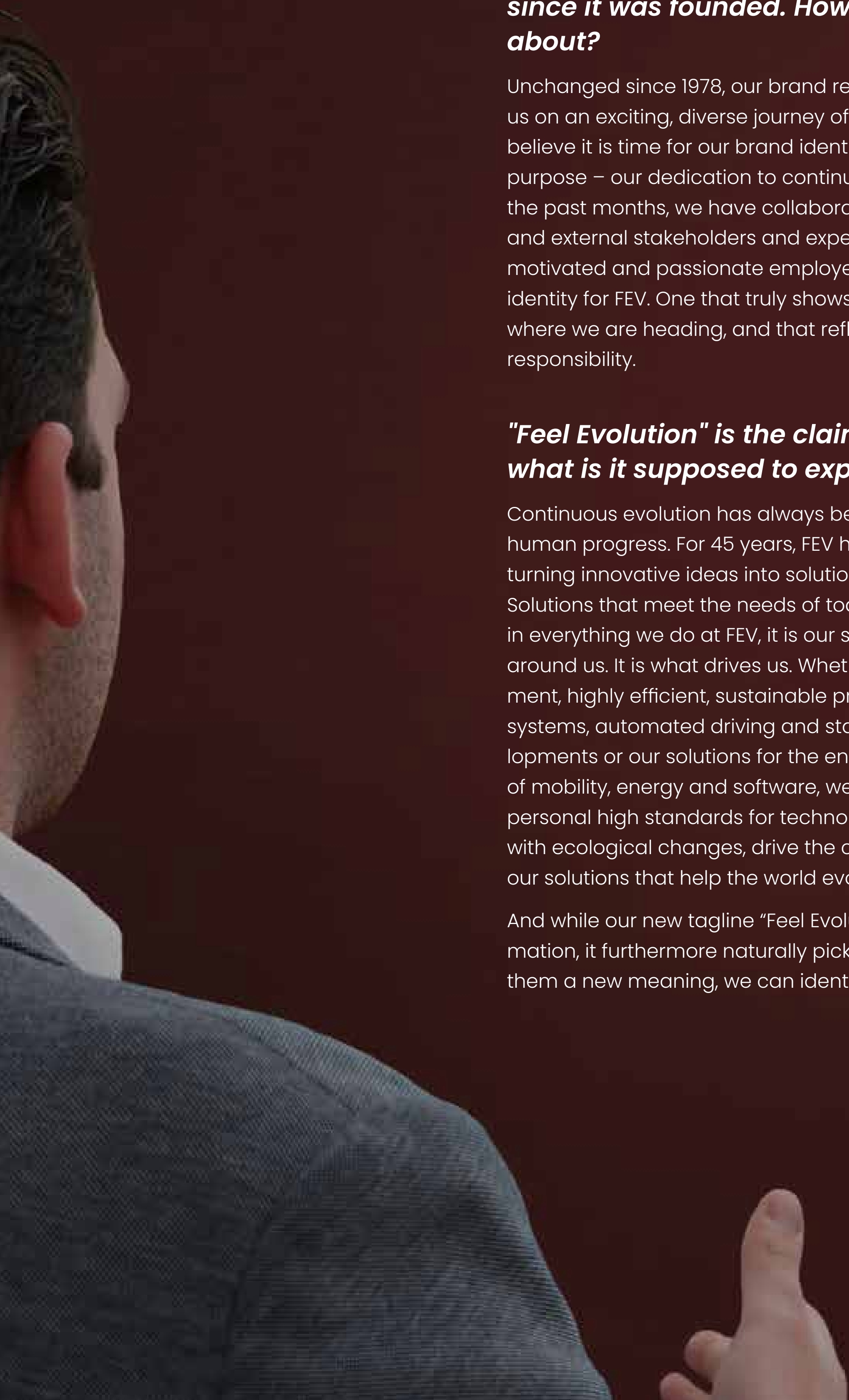
#1
Rebranding Interview with Prof. Stefan Pischinger



Stefan, FEV has undergone its first rebranding since it was founded. How did this step come about?

Unchanged since 1978, our brand represents and accompanies us on an exciting, diverse journey of developing solution. Now, we believe it is time for our brand identity to more accurately reflect our purpose – our dedication to continuous evolution. Therefore, during the past months, we have collaborated with a multitude of internal and external stakeholders and experts, as well as our own highly motivated and passionate employees. The result: A new corporate identity for FEV. One that truly shows who we are as a company, where we are heading, and that reflects our corporate social responsibility.

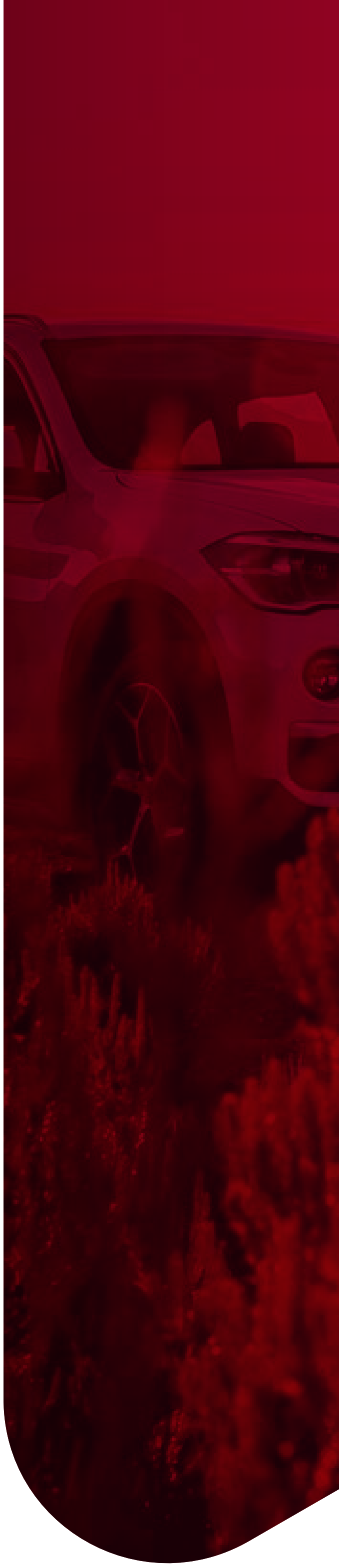
"Feel Evolution" is the claim of the rebranding – what is it supposed to express?

Continuous evolution has always been and remains crucial to human progress. For 45 years, FEV has embodied this principle – turning innovative ideas into solutions that set industry standards. Solutions that meet the needs of today and tomorrow. Evolution is in everything we do at FEV, it is our spirit, you can feel it everywhere around us. It is what drives us. Whether complete vehicle development, highly efficient, sustainable propulsion systems, battery systems, automated driving and state-of-the-art software developments or our solutions for the energy sector – in our core fields of mobility, energy and software, we never stop evolving. Our personal high standards for technological improvement, along with ecological changes, drive the continuous development of our solutions that help the world evolve.

And while our new tagline "Feel Evolution" represents FEV's transformation, it furthermore naturally picks up the letters F, E and V, giving them a new meaning, we can identify with and that is future proof.

Professor
Stefan Pischinger
President and CEO
of the FEV Group

»For 45 years, FEV has been turning innovative ideas into solutions that set standards in the industry and meet the needs of today and tomorrow.«



The logo has a significant impact on the image of a company – what distinguishes the new logo?

Absolutely right, the new logo reflects what FEV stands for today and is designed to appear more human. Starting with the "F", you see that we have introduced a rounded corner. This reminds us of smart technology made for humans. Think about a smartphone, a voice assistant, a technology that is designed for humans featuring pleasant haptics. The twisted "e" represents our creativeness and our innovative spirit. The upward motion gives it a positive appeal. We also animate it to represent forward motion and continuous progress. The "V" in contrast is sharp and stands for trust and reliability.

Has the rebranding process already been completed?

The roll-out in October 2022 was just the beginning. Being present at more than 40 locations worldwide, there is much work ahead of us which takes some time. With focus on a sustainable procedure, we have decided to phase in the brand rollout over the upcoming months.

How does this timing affect sustainability?

As mentioned, we have made a conscious decision to roll out our new brand judiciously over the coming months. This will ensure that we deplete existing inventories of material in a resource-conscious way, and do not have to replace them before their end of lifetime.

What does the rebranding mean for customers, what will change for them?

The whole rebranding process is more than an updated brand identity. It is a commitment to our customers to foster sustainability and greater quality of life for all through innovation. So, our work quality will stay on the same high level which our customers appreciate. However, the fields in which we offer high-class solutions to our customers continuously expand.

Thank you for these exciting insights!

feel evolution

FEV

We drive innovation to help the world evolve.

#2

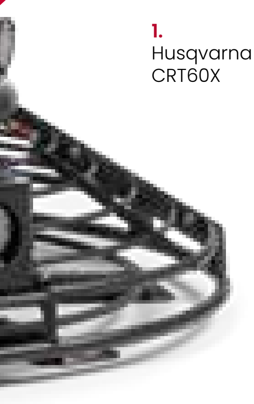
Fuel cells – a powertrain solution for zero-emission non-road mobile machinery

The current trend towards zero-emission vehicles has taken hold also in the field of non-road mobile machinery (NRMM). Traditionally, NRMMs have been equipped with diesel-fueled powertrains. The current trend is leading to stricter emission standards also for NRMMs. In the first cities, e.g. Oslo or Los Angeles, NRMMs must be 100% emission-free from 2030 onwards.

In this study, a concrete placement machine from Husqvarna (Figure 1) is considered. The trowel model is designed to finish concrete slabs between 2,000–4,500 m².

The process of finishing concrete with a trowel is dependent on the state of curing of the concrete. The finishing process can be divided into two steps, panning with discs in an early curing stage and troweling with blades in a later curing stage. Each step normally consists of two or three full passes to finish the whole slab. Between each pass, the operator will have to wait before moving to the next step. The waiting time depends on multiple variables, such as ambient temperature, wind speed and slab construction, etc. One pass can take everything from 5–25 minutes, depending on size and the state of concrete curing, and the waiting time can differ between five and more than 60 minutes.

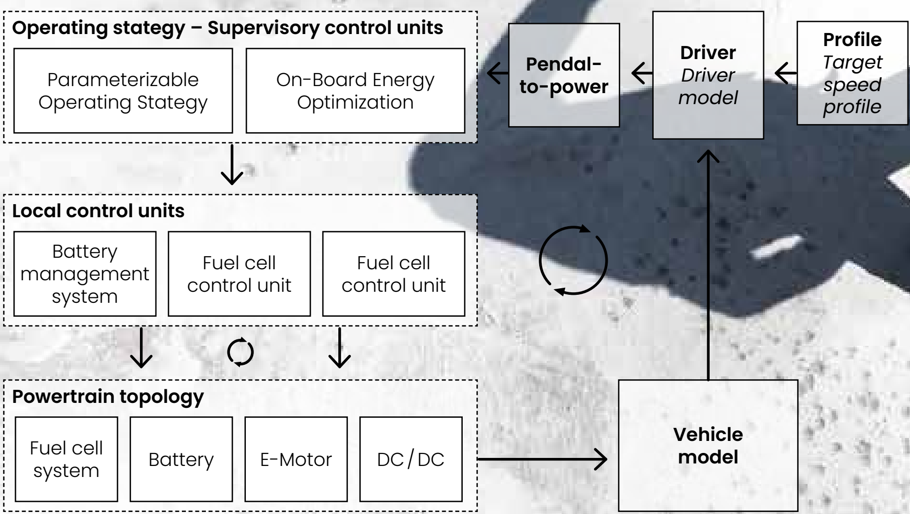
When the time is right for the next pass, the machine must be prepared and ready to do a full pass. Precise timing is so important that a backup machine is always nearby in case of a breakdown on the main machine on most construction sites. The requirements for operating and refueling time are within a narrow scope. The machine must be able to operate for at least 45 minutes at a time, and refueling may take a maximum of four hours. In shift operation, however, where the machines are in use for up to twelve hours a day, the actual refueling interval can be significantly shorter. The operating temperature window is -10 to 50 °C.



1.
Husqvarna CRT60X

Comparison battery electric vs. fuel cell electric propulsion

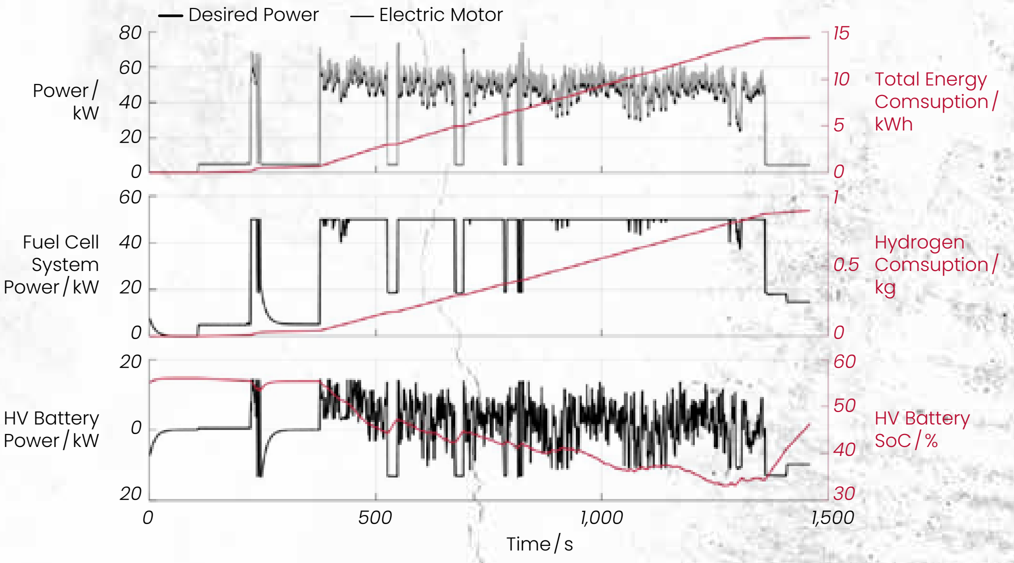
To determine the required fuel cell power, battery capacity and hydrogen storage capacity, a 0D model of the propulsion system was created within the FEV simulation framework (Figure 2). Measured load profiles of customer-owned machines are used for the use case and cycle simulation. Based on the average power consumption of those cycles, a fuel cell system with a system power of 50 kW was selected. The main task of the battery is to cover the peak power request with a defined maximum state of charge (SoC) drop of 30%. Preliminary investigations based on the given requirements for the battery that the limiting factor of the battery is the power and not the energy content. Therefore, a NMC battery with a nominal energy content of 2.58 kWh was chosen. This battery has a peak power output of 15 kW and allows a continuous power output of 10 kW. The applied hybrid strategy tries to keep the SoC of the battery at around 55%.



2.
Modular simulation environment for various propulsion systems

Figure 3 shows the results for a typical cycle in panning mode. The simulation shows that the powertrain sizing fulfills the specified requirements. The total energy consumption is 14.4 kWh or 0.9 kg hydrogen in approx. 24 minutes of operation. Assuming a required total operation duration without refilling/recharging of 60 minutes, 36 kWh of usable battery capacity or 2.3 kg of hydrogen will be required.

3.
Cycle simulation



Based on an assumed depth of discharge (DoD) of 60 %, a charge efficiency of 90 %, and power densities of 140 Wh/kg and 200 Wh/l, the required battery capacity and resulting weight and volume can be calculated. The results, assuming a SoC operation window from 80 to 20%, are shown in Figure 4.

Operation duration	45 min	60 min
Battery capacity	45 kWh	60 kWh
Battery weight	321 kg	429 kg
Battery volume	225 l	301 l
Charge duration (22 kW charge power)	82 min	109 min
Charge duration (50 kW charge power)	36 min	48 min

4.
Battery characteristics for the concrete trowel

An expected battery lifetime of 5,000 hours will result in 180 MWh energy throughput and 4,000 full cycles for the 45-kWh version and 3,000 full cycles for the 60 kWh version.

The weight of the resulting battery, as shown in Figure 4, is approx. 35% of the current operation weight of the entire trowel. Figure 5 shows a comparison of the weight impact by replacing the diesel engine with either a fuel cell or a battery. With regard to the fuel cell, it should be noted that the exemplary system already contains a galvanic isolated boost DC/DC and a very robust IP certified housing. Potential for weight reduction can be expected.

	Battery		Fuel Cell	
Removed diesel engine	-267 kg	-155 l	-267 kg	-155 l
Removed charge air cooler	-5 kg	-40 l	-5 kg	-40 l
Removed diesel tank	-53 kg	-55 l	-53 kg	-55 l
H_2 Tank			+55 kg	+110 l
Fuel Cell			+230 kg	+230 l
Battery	+429 kg	+301 l	+25 kg	+20 l
DC/DC	+25 kg	+15 l	+25 kg	+15 l
Electric motor & inverter	+80 kg	+39 l	+80 kg	+39 l
Additional weight	**+209 kg**		**+90 kg**	
Additional volume		**105 l**		**164 l**

5.
Weight comparison battery vs. fuel cell electric powertrain

In the case of the concrete trowel, the required power correlates quite linearly with the machine weight since the entire weight is carried by the rotating rotors. The additional weight of 90 kg, in case of a fuel cell increases the average power by 3 kW (185 g H_2 per hour). In case of a battery-powered machine, the average load increases by 6 kW due to the additional weight of 209 kg. To compensate for this, the tank and battery capacity must be increased. In case of the battery electric version, this will result in an additional weight of approx. 43 kg and an additional volume of 30 l. In case of the H_2 tanks, the extra weight is negligible, the additional volume is 8 l (pure H_2 volume at 350 bar). Considering this, as well as the required charging duration of at least 48 minutes with 50 kW charge power, a fuel cell powertrain seems to be the more suitable solution for this application.

Technical feasibility and integration concept

For the concept study, a 350 bar cylinder with a diameter of 399 mm and a capacity of 1.8 kg was chosen. The capacity is sufficient for more than 45 min of operation. If required, a second tank with either 1.8 or 0.8 kg could be placed above the first tank to increase the operation duration to 70 or 96 minutes.

Fuel cell system positioning and influence on center of gravity

For this study, 6 different fuel cell types or configurations from 5 suppliers have been considered. In this application the center of gravity (COG) needs to be considered. Table 6 shows the influence of exemplary fuel cell system positions on the initial COG (COG1). For comparison, an operator leaning forward shifts the center of gravity by approx. 13 mm to the front. Depending on the positioning 20 to

6.
Influence of fuel cell system position on COG

Option	A	B	C
Fuel cell system position	Vertical behind seat	Horizontal below seat	Vertical below seat on frontside
Distance to COG1	-526 mm	-226 mm	104 mm
ΔCOG	-98 mm	-42 mm	19 mm

40 mm can be compensated by clever arrangement of other components like the hydraulic pump and the electric motor. The remaining 58 mm (in case of position A) must be compensated by a counterweight of 140 kg in the front area of the machine.

To avoid additional counterweights, the fuel cell is positioned below the operator seat (Option C). This excludes 4 of the 6 fuel cell systems, as they do not fit between the main nor the upper frame of the machine. The selected fuel cell system meets the standardized installation space requirements from the EU project StaSHH.

»Mobile machines of the future must be thought of holistically with the construction site of the future in mind.«

Selected concept

Due to a clever arrangement of the components, there is no shift of the COG and therefore no counterweight is necessary. Figure 7 shows a cross-section of the selected concept. The FCS is positioned vertically in the front area below the seat. COG of the FCS is left of the machine COG and compensates the COG shift of electric motor. The battery and PDU can be positioned above the electric motor, between FCS and tank.

The fuel cell operates at a maximum temperature of 70 °C and requires a coolant inlet temperature of max. 60 °C. Taking into account an ambient temperature of up to 50 °C, a considerable radiator size is required. To gain sufficient installation space for the radiator, the retardant tank is moved to the position of the former fuel tank.

The radiator can then be placed on the left side of the operator seat. The radiator for hydraulic circuit can be left in its original position to the right of the operator. The size of the depicted radiator is 650 x 600 mm. Simulations performed by the supplier show a cooling capacity of approx. 50 kW at 45 °C ambient temperature with a standard fan. To ensure sufficient cooling capacity even at 50 °C, an optimization of the radiator fan is required. Figure 8 shows the positioning of the radiator.

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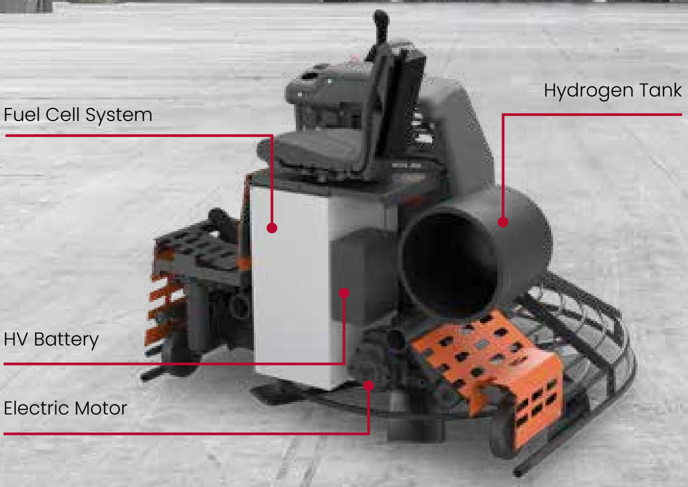


7.
Cross section of the selected fuel cell propulsion concept for the concrete trowel

8.
Position of the radiator

Outlook and conclusion

Electrification offers an increase in efficiency in both applications already in the first step, as idling phases of the diesel engine during handling before and after use are eliminated, since the hydraulic system can be powered by the hybrid battery.

In a next step, it makes sense to replace the hydraulic system and drive the rotors electrically. This results in advantages in terms of weight and installation space, but more importantly also in an efficiency advantage during operation.

Electrification of NRMMs will be essential in the coming years to enable local emission-free operation. On construction sites with limited power grid connection, local emission-free electricity generation will become necessary in future. This can also be achieved by hydrogen and fuel cells using trailer-based solutions to provide electricity to charge the batteries of smaller NRMMs and to refuel bigger NRMMs with hydrogen. Also, mobile machinery of the future must be thought of in a holistic approach with the construction site of the future.

#3

BiFoilStack – novel cell and stack design with compound-foil-based bipolar plates for heavy-duty fuel cell systems

ty

The transport sector is one of the largest drivers of climate change. While the transition from fossil sources to sustainable solutions is in full swing for passenger cars, the heavy-duty sector is still lacking behind. Fuel cells are widely recognized as a corner-stone for the energy transition of the heavy-duty sector. However, manufacturability and durability are current challenges for the application of fuel cells within heavy-duty vehicles. Currently, polymer-electrolyte-membrane (PEM) fuel cells are the favored fuel cell type in transportation. Especially, the bipolar plates (BPP) are one major component for improvements in terms of manufacturability and durability. They are commonly made from either metallic or graphite material. Both have their individual advantages and drawbacks. Graphite plates display excellent durability, but they are relatively thick, reducing the power density of the fuel cell system. Moreover, the manufacturing processes are not suited for cost-effective, large-scale production. Metallic bipolar plates are much thinner, and the manufacturing processes are easily scalable and cost-effective. However, the humid and acidic environment within the fuel cell leads to corrosion of metallic plates and coatings or high-grade materials must be used.

To overcome these challenges and to combine the advantages of metallic and graphite bipolar plates, the Fraunhofer UMSICHT developed a novel process for graphite-polymer composites, suitable for the large-scale production of PEM fuel cell BPP.

Within the publicly funded project “BiFoilStack - Development of stack designs for LT-PEM fuel cells with novel compound bipolar foils” innovative stack and assembly concepts will be developed that exploit the design flexibility of thermoplastic bipolar foils.

Heavy-duty stack requirements

Fuel cells for heavy duty applications demand high durability and reliability, low production cost, high efficiency, as well as high power density. To achieve these targets within BiFoilStack, the following solutions will be used:

- Durability: use of graphite-polymer composite foils to mitigate bipolar plate corrosion and flow field design to reduce mechanical and chemical degradation effects on MEA level.
- Power density: low substrate thickness of BPP in the range of metallic BPP and much thinner compared to conventional graphitic plates as well as high utilization of the total cell area for power production.
- Production costs: roll-to-roll production process for BPP without coating and novel stack concepts, based on the design freedom arising from the BPP material
- High efficiency: innovative flow field design with improved mass transport characteristics and reduced electrical resistances

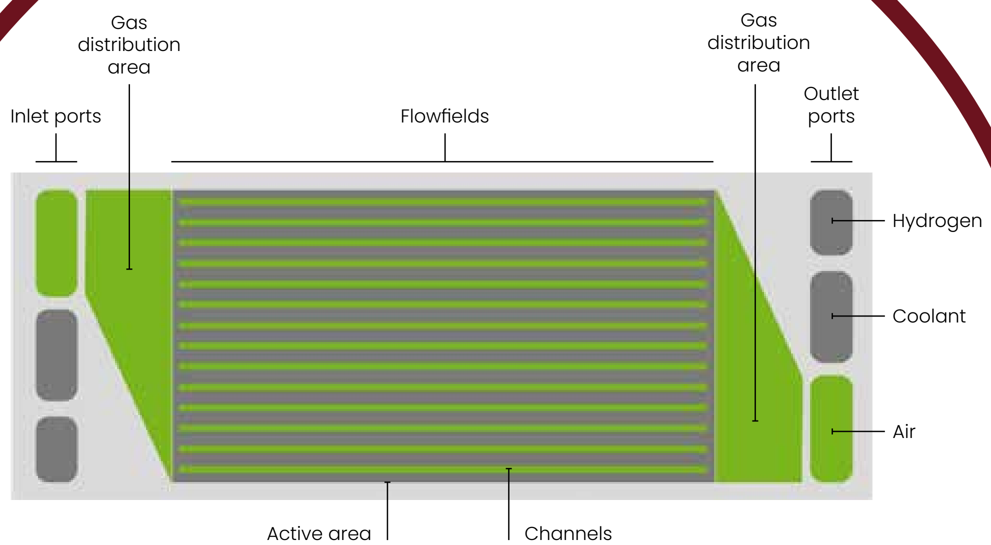
Besides the above general targets, specific requirements, depending on the application, must be specified to start the design process. To derive these, the share and CO_2 emissions of new heavy-duty vehicle sales was analyzed first.

It was found that more than half of the CO_2 emissions of related to the new sales of heavy-duty vehicles can be attributed to 4x2 tractors with more than 16 tons. This vehicle group typically has a combustion engine power output between 250 kW and 380 kW, while the most sold engine has a power rating of 340 kW. Hence, a fuel cell system net power output of 300 kW is targeted since peak power requirement can be reduced via electrification and hybridization. To account for the auxiliary power consumption of the fuel cell system, a stack power of 340 kW is targeted.

For the definition of the available packaging space within the HD truck, the standard fuel cell module sizes from the publicly funded research project StasHH (www.stashh.eu) are used. The appropriate standard size for engine bay installation of a 40-ton truck is 1,360 x 1,020 x 700 mm. This box must accommodate the fuel cell stack as well as all auxiliaries.

Taking into consideration current limitations of power electronics, vehicle electronic architecture, available components, and size constrains the following high-level stack specifications were derived:

- Number of stacks: 2
- Cells per stack: 400
- Active area per cell: 350 cm²
- Design operating point: 0.6 V @ 2 A/cm²
- Stack power: 2 x 168 kW = 336 kW



1.
Schematic structure of a fuel cell bipolar plate

Conceptual cell design

The design of a cell can be decomposed into three main areas: I) Channels, II) Hydrogen, air, and the resulting coolant flow field, and III) ports.

Design focus is the flow field since it is most crucial for the performance of the cell. The fluid supply must be as homogeneous as possible since the electrochemical re-action rates mainly depend on the local species concentration. To achieve this, most fuel cells utilize a gas distribution area (Figure 1). Current state-of-the-art cells (Toyota, Hyundai) utilize a flow distribution area and exhibit a ratio of total cell area to active area from 1.9 to 2.3.

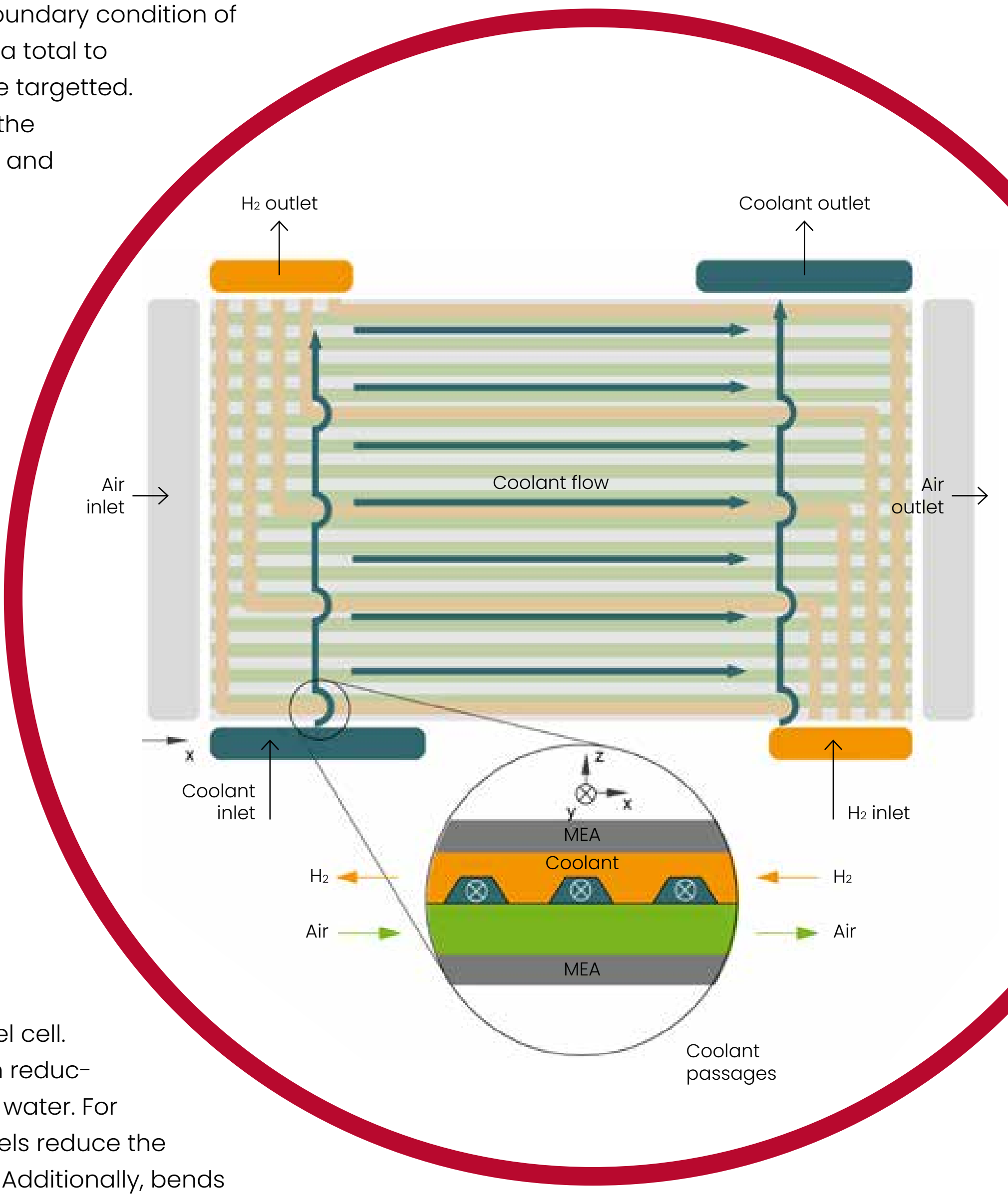
Taking the power density target of 5 kW/l and achievable cell pitch of 1.8 mm from the material boundary condition of the BiFoilStack project into account, a total to active cell area ratio of <1.32 must be targetted. This can only be achieved through the removal of the gas distribution area and high current density operation.

High-level flow field definition

For the definition of the cell's ports and channels, the high-level concept of the flow field must be defined. To cope with the high production rates of water, air and coolant are arranged in counter flow configuration to reduce liquid water formation due to the increasing temperature downstream the channel. Air and hydrogen should be in counter flow to enable internal humidification, especially at the air inlet where this effect is most pronounced.

The cathode flow field is the most critical one for a high performing fuel cell. Reasons for this are the slow oxygen reduction reaction and presence of liquid water. For efficient water removal short channels reduce the water accumulation in the channel. Additionally, bends in the channels are avoided to further reduce water accumulation. Therefore, the cathode flow field will have straight, parallel channels, which are directly connected to the port without any gas distribution area (Figure 2).

2.
High level cell concept for all flow fields



The hydrogen flow is realized in counter-flow to the air flow to utilize internal humidification. To connect the inlet- and outlet ports and realize a mostly counter-flow arrangement the hydrogen channels are guided through the flow field in a Z-shaped fashion. The vertical hydrogen channels at the air inlet and outlet further aids the internal water recirculation through the hydrogen channels due to the long contact times.

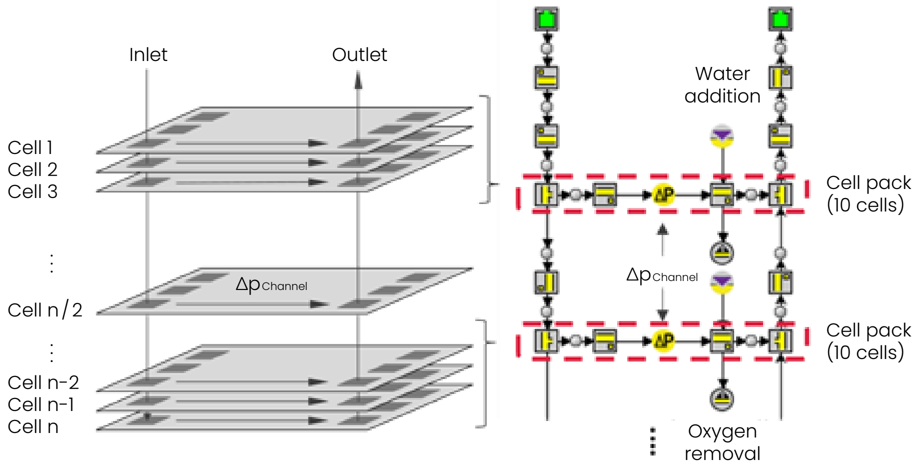
For the introduction of the coolant between the cathode and anode appropriate openings must be created to guide the coolant in between the bipolar plates. The hydro-gen channels are used for these openings to not disturb the air flow.

Port definition

Another crucial aspect of the cell design are the inlet and outlet ports for hydrogen, air, and coolant. Main task of the ports is the distribution of the fluids into the individual cells while low-pressure losses and cell-to-cell variation are desirable.

For studying the impacts of the inlet and outlet ports on the power density as well as cell-to-cell variation, a 1D flow model was developed (Figure 3).

The optimization of the cathode ports is shown in Figure 4 for an inlet port area of 14.5 cm² and channel pressure losses of 200 mbar. The upper graph depicts the maximum mass flow deviation



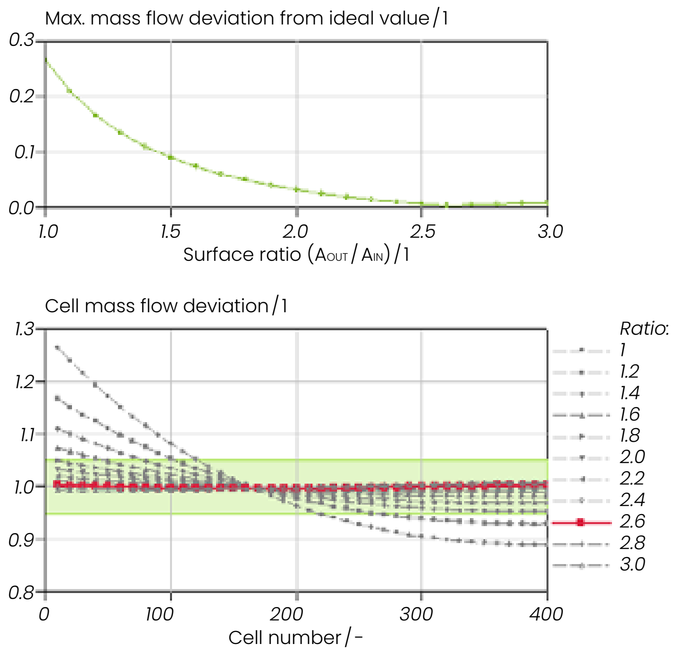
3.
Left: Schematic representation of a fuel cell stack.
Right: Modelling approach for port design

»In the design of a cell, the coolant flow field with its influence on the with its influence on the cell performance is of the utmost importance.«

of a cell pack versus the area ratio of outlet to inlet port. In the lower graph the mass flow deviation of the individual cell packs is shown.

As Figure 4 shows, the mass flow deviation reduces with increasing area ratio, i.e., outlet area, until a minimum deviation is achieved for an area ratio of 2.6. Reason behind this behavior is the varying static pressure difference between the cells, which is driving the mass flow. In the ideal case (ratio = 2.6) the static pressure difference is equal for all cells. During the port design, the static pressure in the outlet port can be controlled via the adjustment of the dynamic pressure, i.e. fluid velocity through the adjustment of the port's cross section. By optimizing the cross section, the cell-to-cell variation can be minimized.

4.
Results of cathode port definition simulation study for an inlet port area of 14.5 cm²



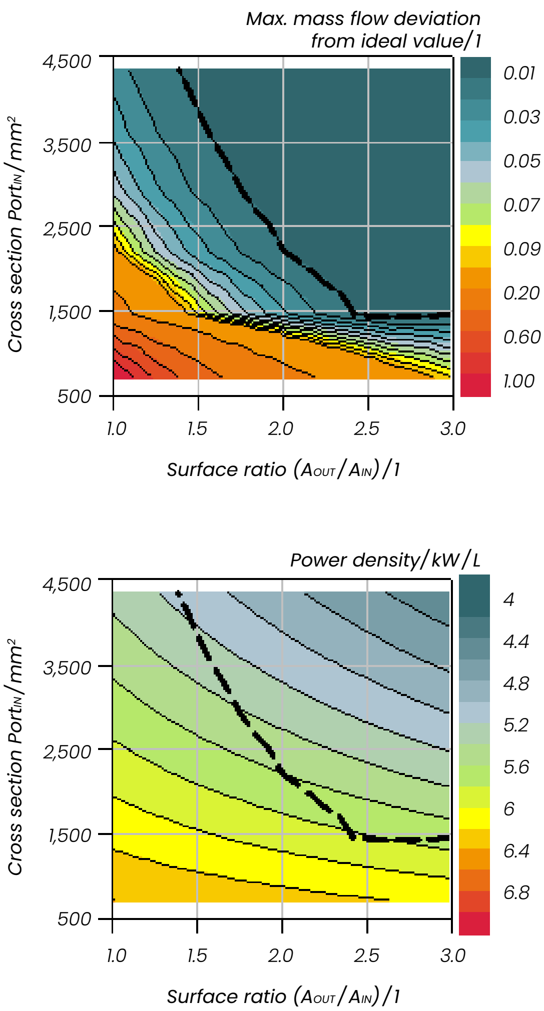
To study the impact of the inlet port area and to derive the ideal overall port area with respect to the power density of the stack, the results of all conducted simulations are shown in Figure 5.

The map shows that the cell-to-cell variation increases with decreasing inlet port area at constant area ratio. This is due to the increasing fluid velocity, caused by the decreasing port area and therefore higher dynamic pressure. This leads to a larger static pressure difference between the individual cells and higher mass flow deviation. To compensate the impact of the dynamic pressure with decreasing inlet port cross section, the outlet port area must be increased continuously to keep the cell-to-cell variation constant.

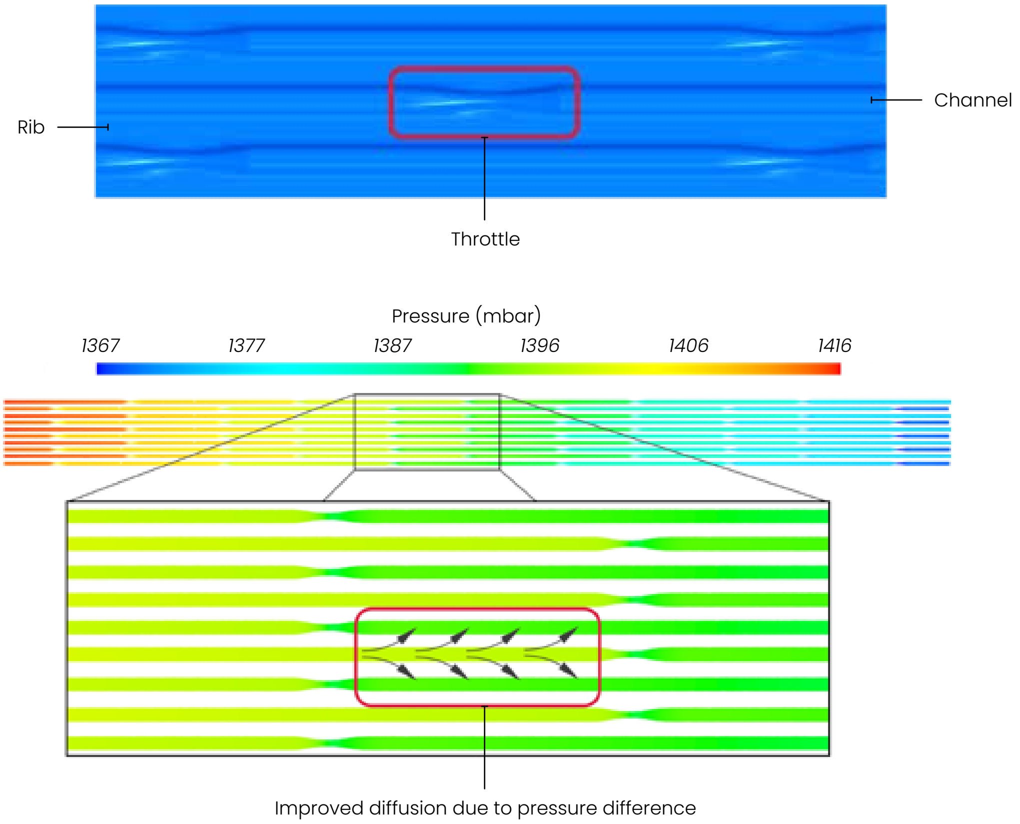
Since the ports are necessary but do not contribute to power generation, it is desirable to reduce the overall port cross section, while keeping the cell-to-cell variation at a minimum. This relation is shown in the right graph of Figure 5. At constant cell-to-cell variation (dashed line) it becomes obvious, that an optimum of the port's cross sections exist in terms of power density. In the present case, this optimum can be found at 1,450 mm² inlet port cross section and outlet-to-inlet area ratio of 2.4.

Channel definition

Besides the channel cross-section the shape along the channel direction can also be used for the optimization of the fuel cell's performance. Due to the high production of liquid water, measures must be taken to discharge it. Multiple tapers along the channel have proven suitable for such a task since the increased pressure upstream of the taper facilitates diffusion under the ribs and water removal. Such tapers are shown in Figure 6.



5.
Characteristic maps showing the maximum mass flow deviation between the cells and stack power density (active area plus joint port area). The dashed line shows the iso-line at 1 percent mass flow deviation.



6.
CFD simulation of flow field with alternating throttle positions in parallel cathode flow field

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Summary

Novel bipolar plate materials that combine the advantages of metallic and graphite plates have the possibility to be transitioning technologies during the scale-up of fuel cell technology into the market. The careful design of the cell, exploiting the positive features of the material, can further improve the performance and power density. This was shown on the example of the port design and high-level cell concept. The power density could be increased to >6.4 kW/l, considering the active area plus joint port area, despite the currently 2.5 times higher material thickness compared to metallic plates.

Innovative solutions for the challenges of intelligent mobility

feel evolution

FEV.io

FEV.io addresses the increasing requirements, needs and the pace of development in the field of intelligent mobility. Through our deep understanding of software and electronics in combination with detailed know-how in all vehicle areas that are essential for the development of intelligent mobility solutions, we offer our customers first-class engineering services. The portfolio of FEV.io covers seven domains: Systems Engineering, Functional Safety & Cyber Security, Connected Mobility, ADAS/AD, Infotainment, SW & EE Platforms, SW & EE Integration.

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Thema des Artikels

#4
Thermal integration of high-speed electric machines in electric drive trains

The automotive landscape is currently changing rapidly towards emission-neutral electric vehicles. At the moment, electric vehicles predominantly use permanent magnet excited electric traction machines due to their high efficiency and power density. However, high-energy permanent magnets rely on rare earths, which are considered as critical raw materials and are sensitive to geopolitical trends. In addition, these magnetic materials are not consistent with a sustainable circular economy.

»FEV has developed a thermal conditioning approach that improves the efficiency and overload capacity of electrical machines«

FEV sees two ways to address this issue. First, electric machines can be designed to be completely magnet-free, but this comes with a reduction in power density due to the lack of the inherent magnetization. An alternative is to use electric traction machines with reduced rare earth magnet content or to increase the power density to reduce the amount of material used for the same power output. The power density of an electric machine can be increased for the same package space either by increasing the speed and/or by increasing the torque.

With the approach of increasing power density through high speeds, effects occur that are not limited to the electric machine only but can affect the entire drive train. The limit for the maximum speed of electric machines is the rotor circumferential speed. The limit of economically feasible rotor circumferential speeds is typically between 100 m/s up to 150 m/s. Two-stage gearboxes with an intermediate shaft are state-of-the-art. As the number of gear stages increases, the efficiency of the overall gearbox decreases. As long as no additional intermediate shafts are added, the costs and losses do not change significantly. With a gear ratio of 1:4 per stage, an overall gear ratio of 1:16 can theoretically be achieved. However, ratios above about 1:10 involve additional expense. For this reason, FEV assumes that the speeds for electric traction machines will range between 20,000 rpm and 30,000 rpm in the near future.

Increasing the currents and thus the current density leads to an increase in torque, but at the same time to additional copper losses, which must be dissipated by improving the cooling system. Alternatively, a higher winding temperature can be permitted by using higher-quality insulating materials. With current designs, the vehicle reaches the end of its service life before the insulation system fails. This provides thermal headroom that can be used to increase the winding temperature without using higher-grade materials.

As higher power and thus higher losses are concentrated in a smaller volume, cooling becomes increasingly important. One promising approach for FEV to achieve an effectively higher power density, and thus a lower permanent magnet content and a better overall performance, is the active thermal optimal operating of the dedicated designed electric machines. Key aspects in the design and development of active thermal conditioning are the extended and increased overload capability, the increase of the continuous operating range and the active thermal field weakening, which FEV already introduced.

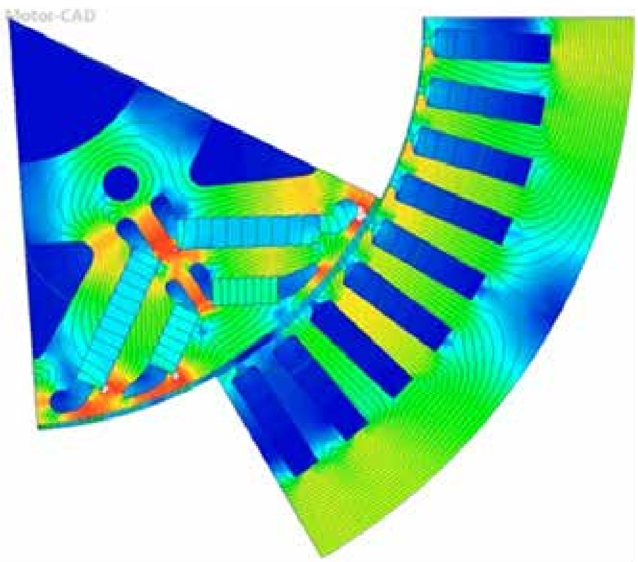
FEV has developed a thermal conditioning approach to improve the efficiency and overload capability of electric machines. In order to take full advantage of thermally active conditioning, transient and independent temperature control must be ensured in the components of the electric machine. The faster the temperature can be adjusted, the faster the targeted operating parameters can be achieved and the required efficiency or power is available. For this purpose, a simulative comparison is made between a high-speed electric machine newly developed by FEV and a state-of-the-art traction machine, both with a peak power of more than 150 kW. The two machines are equipped with a housing water jacket cooling system. Electromagnetic and thermal simulations are performed, and it becomes clear that the new machine developed by FEV has a more dynamic thermal behavior compared to the state-of-the-art machine. This can be explained by the lower thermal masses of the stator and rotor as well as by a higher loss density. Considering the higher speed range of the newly developed machine of up to 24,000 rpm, the loss density will be even higher in wide operating ranges, which further increases the thermal dynamics.

Design of high-speed electric machines at FEV for thermally active conditioning

For the design of electric machines, FEV has developed a design tool for determining the main dimensions. This is used in a first step of the design tool chain. Once the dimensions are defined and the rotor topology is determined, iterations follow to achieve the application-specific requirements. The entire tool chain consists of requirements definition, basic dimensioning, electromagnetic and thermal simulation iterations, and finally mechanical simulations with potentially further iterations between the different disciplines.

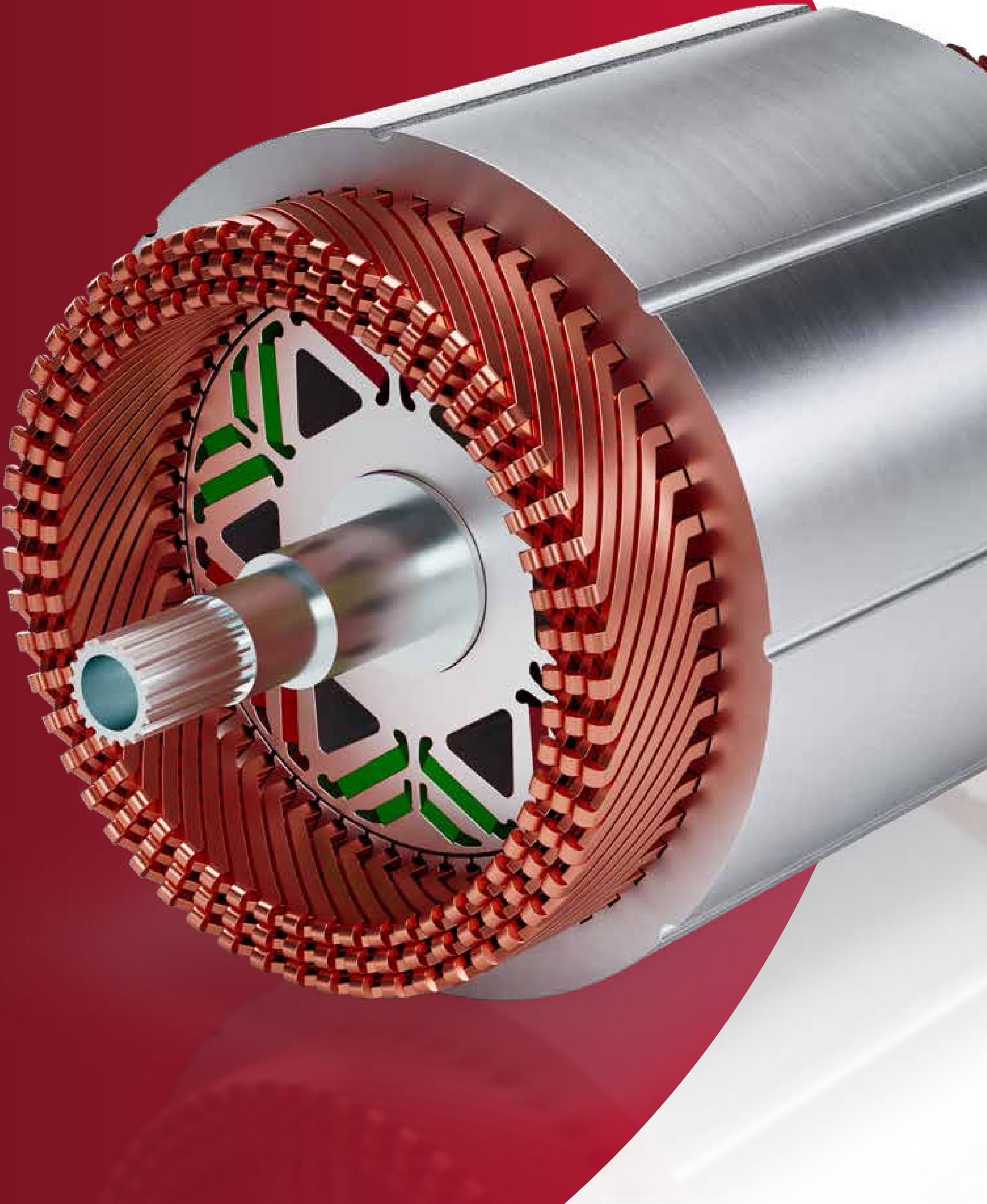
The rotor topology with a double V-shaped magnet arrangement, as shown in Figure 1, is chosen because of the high efficiency and the desired torque-speed characteristics. Shape-optimized flux barriers, which ensure mechanical stability even for higher speeds and offer the possibility of coolant flow through these, are included in this design.

A main requirement for the electromagnetic and thermal design is that the temperature limits of all components are maintained. In permanent magnet excited machines, these are usually the insulating material system or the permanent magnets. One goal of the developed high-speed machine is to minimize thermal time constants and provide independent component cooling, especially for the magnets in the rotor. Following the electromagnetic and thermal design iterations, a mechanical evaluation and optimization of the rotor geometry is performed to ensure speeds above 20,000 rpm. One major topic are the dedicated magnet cooling channels close to the magnets. On the one hand, these channels must be wide enough to effectively conduct the coolant and fulfill the magnetic function of the flux barrier. On the other hand, channels that are too wide will weaken the mechanical stability.



1.
Exemplary flux density distribution in the new electric high-speed machine developed by FEV.

2.
Electromagnetically active components of the high-speed machine developed by FEV, with hairpin winding and a rotor topology with a double V-shaped magnet arrangement with flux barriers for direct magnet conditioning. The cooling channels of the stator are not shown.



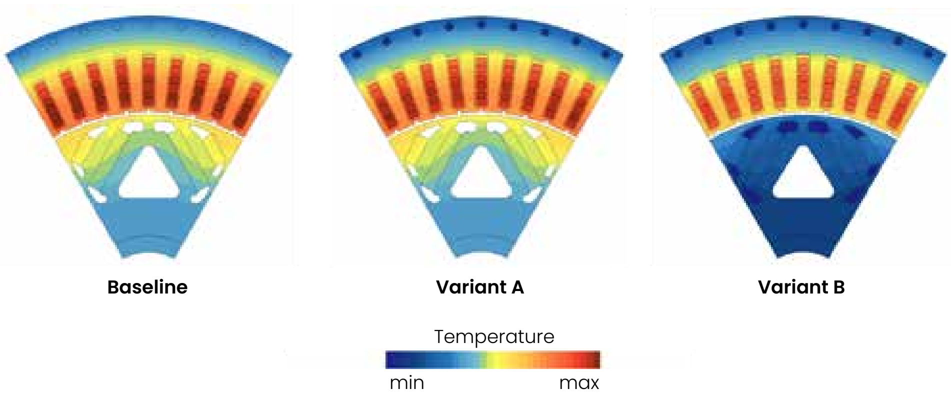
The active components of the high-speed machine are shown in Figure 2. In order to determine the performance in continuous operation, initially only a state-of-the-art water jacket cooling system is used. This is implemented for simulation in a thermal network model and parameterized with heat transfer coefficients determined from fluid dynamics simulations.

Thermal modeling of different cooling concepts for electric machines

During development of electric machines, the electromagnetic and thermal interactions must be taken into account at an early design stage. For newly developed cooling concepts, it is not trivial to determine the actual heat transfer coefficients. On the one hand, computationally intensive and accurate computational fluid dynamics simulations of these concepts can accurately evaluate the resulting temperature distribution in the electric machine, as well as the spatial cooling capability. On the other hand, these simulations are computationally much more expensive than lumped parameter thermal network models. In particular, if different cooling topologies, complete efficiency maps, and entire drive cycles are to be evaluated in the preliminary design phase, it is not efficient to perform coupled electromagnetic and thermal fluid dynamics simulations.

In order to create a reliable simulation basis, the computationally intensive fluid dynamics simulations are therefore performed initially only for a representative steady-state operating point. These simulations give a good indication of the heat transfer coefficients from the components of the electric machine to the cooling system. These coefficients are used to parameterize the lumped parameter thermal network model. A network model is set up that represents the entire electric machine in the axial and radial directions. Material parameters and heat transfer coefficients are considered. Effective thermal conductivities for the winding insulation material system and for the magnetic steel sheets in radial and axial directions are used to represent the actual properties. A speed-dependent thermal conductivity in the air gap of the electric machine is implemented.

In this article, FEV investigates three cooling concepts. The fundamental differences between the cooling systems are on the one hand the type of coolant and on the other hand the position of the cooling channels. For the Baseline, a housing water jacket cooling with a water-ethylene glycol mixture is selected, which represents the current state-of-the-art. For Variant A, additional direct stator oil cooling is added, and for Variant B, an additional direct rotor oil cooling is added as well, which is intended to enable magnet conditioning. Due to dielectric properties, an oil-based coolant is used. Direct stator oil cooling and rotor conditioning are not yet widely used in electric traction machines but have the advantages that the coolant is closer to the components to be cooled or conditioned, thus ensuring more dynamic thermal behavior, more precise component temperatures, and lower temperature gradients within the electric machine. Disadvantages are the higher design efforts and a challenging sealing concept.



The differences between the three cooling concepts are shown in Figure 3. The additional direct stator oil cooling in Variant A has only a minor influence on the rotor temperatures. This can be explained by the high copper losses in the windings, which are located between the stator cooling channels and the rotor. The lower temperatures in the windings are due to the lower effective resistance between the heat source in the winding and the stator cooling system. Further temperature reduction can be achieved by additional direct cooling of the rotor in Variant B. The temperature in the rotor is close to the coolant temperature. The winding temperature also shows a further reduction compared with the Baseline and Variant A cooling concepts.

3.
Resulting radial temperature distribution in the high-speed machine at a steady-state operating point, for the Baseline cooling concept (left), Variant A (center) and Variant B (right).

TEXT

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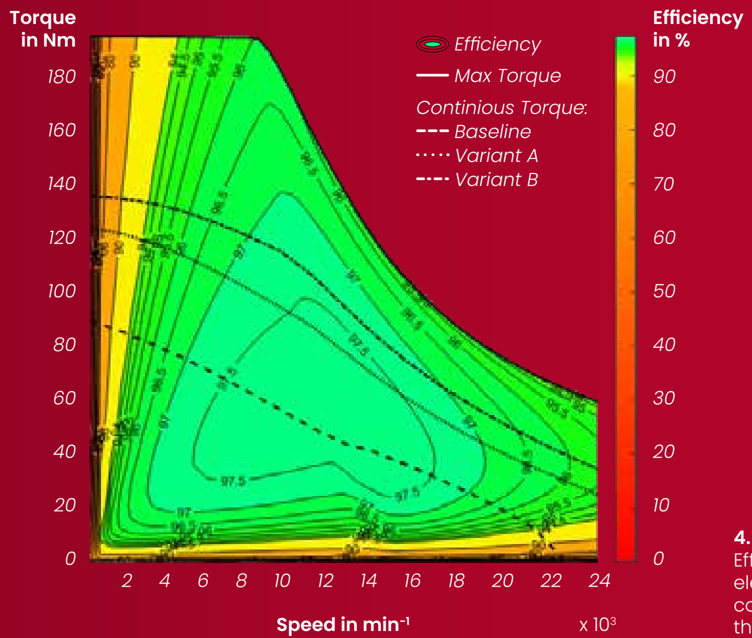
Results

The resulting efficiency map and the respective continuous torque characteristics for the three cooling concepts investigated are shown in Figure 4. The Baseline shows the lowest continuous torque with only about 50 % of the maximum torque in the low speed range. Above 22,500 rpm continuous operation is not possible, which is partly due to the temperature limit of the magnets. Increased continuous operation is possible with the adapted cooling variants. The maximum possible torque is not changed, but the time in which this is available can be extended by better cooling concepts. The continuous torque or power can be significantly improved by using the additional cooling concepts.

By using direct stator cooling in Variant A, an increase in the continuous torque of approx. 50 Nm can be achieved compared with the Baseline concept. This is due to more effective heat dissipation in the winding and thus a better thermal condition in the electric machine. With the additional rotor cooling concept in Variant B, the thermal limitation of the magnets in the high-speed range is further reduced. Due to the good thermal condition of the entire machine, the continuous torque can be improved by another 15 Nm.

The most promising sophisticated double oil cooling with additional water jacket housing cooling concept shows highest potential for dedicated component conditioning. This enables the high-speed concept to be operated in the so called active thermal field weakening range, which ultimately increases the efficiency in drive cycle operation as well as guarantees the overload capability of the compact high-speed machine design.



4.
Efficiency map of the high-speed electric machine and the respective continuous torque characteristics for the three investigated cooling concepts.

#5
Solid-state battery pack design: simply exchanging the cells?

The global trend toward electrification of vehicle powertrains is leading to challenging development targets for energy storage systems. Especially for Battery Electric Vehicles (BEV), which use their high-voltage battery as the sole energy source for traction, the driving range is a key property. The driving ranges demanded today require energy contents of up to 120 kWh for a full-size SUV, and even more for larger vehicles. This will be achieved by increase of energy density in battery cells but also by a higher integration level of battery cells into battery pack.

Innovations in battery cells are the focus of numerous academic, industrial, and government research and development activities. Increasing energy density while maintaining or increasing safety and power density is the focus of new technologies. From these future trends, the great potential of solid-state batteries (SSB) can be deduced.

After explaining the fundamental principles of this cell technology, this article discusses already existing or announced solid-state cells and their special features with a focus on their influences on the battery pack design. The underlying data is taken from a prototype cell of the manufacturer ProLogium, which was developed in the context of a joint cooperation.

Advantages and challenges of solid-state batteries

- \+ Potential to improve gravimetric and volumetric energy density by up to 40 and 70 percent respectively
- \+ Higher thermal stability than liquid electrolyte
- \+ Improved safety (specially under external heating failure scenarios) thanks to replacement of flammable liquid electrolyte with solid electrolyte with higher decomposition temperatures
- \+ Fast charging capability thanks to higher transference number for inorganic solid electrolyte ($t_{Li+} \approx 1$ compared to 0.2 to 0.5 for aprotic electrolytes)

- \- High internal resistance that originates from solid electrolyte degradation at the electrode interface; suitable electrode coatings are needed to impede the side reactions
- \- Production of sufficiently thin solid electrolytes (about 12 μm) with a thickness comparable to the separators
- \- Volume changes of electrodes during cycling causes contact loss between solid electrolyte and electrodes

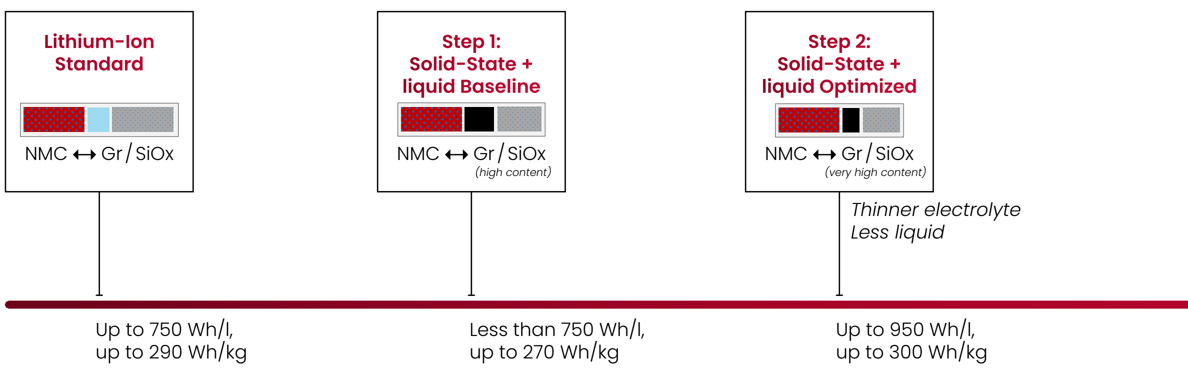
Basic properties of solid-state batteries

Currently, lithium-ion cells with liquid and polymer electrolytes are in use, with the vast majority being liquid electrolyte cells without metallic lithium. The main differences between a SSB and a conventional Li-ion battery (LIB) is the replacement of the separator and liquid electrolyte with a solid-state electrolyte and the use of anodes with higher capacities.

Generally, the target of next generation lithium-ion battery cell development is enabling the use of metallic lithium which is set to increase the energy density. However, since dendrite formation and non-uniform lithium metal electrode position during charging are a serious safety hazard, polymeric and crystalline electrolytes are being developed alongside to increase the safety of using lithium metal anodes.

Conventional batteries contain a graphite anode with a theoretical specific capacity of 372 mAh/g. In the next generation of batteries, Silicon (3,861 mAh/g) or Lithium metal (4,200 mAh/g) anodes with 10-fold higher theoretical capacities are considered to increase the energy density. However, liquid electrolytes react strongly with lithium and silicon, causing low coulombic efficiency and deteriorated battery performance. Solid electrolytes, on the other hand, have the potential to form a stable interface with these kinds of anodes.

For SSBs, sufficient stack pressure is crucial to maintain contact between the cell components.



1.
Roadmap for solid-state cells – evolution and not revolution

However, very high stack pressures can cause short circuits because of the ductility of the lithium metal which can creep through the solid electrolyte's pores. Therefore, the stack pressure needs optimization for each cell chemistry and a stack pressure of about 50 atm has been suggested for sulfide-based electrolytes.

In another approach, a small amount of liquid electrolyte is added to the SSB to keep a good contact with cathode active material components while the cell can perform at lower stack pressures. However, this approach lowers the thermal stability of the battery as compared to all solid-state batteries (ASSB) utilizing purely solid electrolyte.

On the road from conventional LIB to ASSB, a multi-step evolution takes place (Figure 1). Today, ProLogium is also pursuing the second approach of a hybrid solution, in which a small amount of liquid electrolyte is added to the SSB to provide more safety. With this strategy, large cells (>50 Ah) with a high silicon content (>20 percent) in the oxide-based anode can be produced. In the subsequent optimized hybrid step, the silicon ratio is increased towards a pure silicon anode until the anode is replaced by lithium metal with a parallel reduction in the thickness of the solid-state electrolyte. Finally, the ASSB is achieved by omitting the liquid electrolyte.

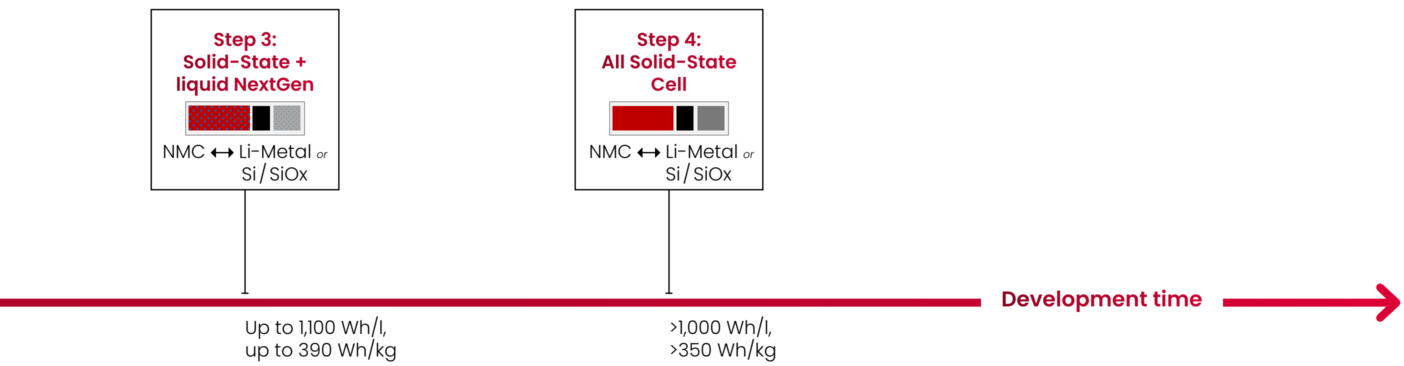
Most commercial SSBs use polymer, sulfide and oxide solid electrolyte. As described above, ProLogium combines oxide-based electrolytes with a high silicon content or a lithium anode, enabling up to 280 Wh/kg in 2022 and >410 Wh/kg in 2025. QuantumScape is developing an oxide-based ceramic electrolyte in combination with an organic liquid catholyte (electrolyte on the cathode side to improve interfacial resistances). Their technology is announced to achieve >400 Wh/kg.

Solid Power is currently working on a 20 Ah lithium-ion pouch cell with a sulfide-based ceramic electrolyte using a silicon-content anode and a high-Ni NMC. Their current target is to achieve 390 to 440 Wh/kg at cell level. SolidEnergy Systems, a spin-off from Massachusetts Institute of Technology (MIT), is pursuing a ceramic-based electrolyte coupled with a liquid catholyte to achieve an energy density >400 Wh/kg.

As can be seen, there is not one unique technology path being followed, but there are currently several different approaches. Although there is a lot of lab-scale activity, manufacturing a solid electrolyte with low impedance and interface resistances, good mechanical strength and high ionic conductivity at low cost remains a major challenge. Nevertheless, many announcements from small start-ups to large manufacturers are focused on the second half of this decade, so the stage is set for a solid-state revolution in the battery industry.

Battery system design based on solid-state cells

Following the presentation of technical insights into SSB technology and activities of cell manufacturers in this field, a battery system will be designed considering the special capabilities and needs of solid-state cells. Aiming to investigate to what extent the cell level properties can be transferred to the pack level, various battery concepts in typical automotive-relevant dimensioning based on different cell formats and with different layouts were considered and evaluated, from which the most promising approach will ultimately be pursued in further design. In this context, the currently available cell technology with 28 percent silicon in the anode and liquid electrolyte content and 615 Wh/l from ProLogium is considered.



Battery development

To improve the swelling-management of the cell in connection with the solid-state technology and to simplify production and development at the module and pack level, a prismatic cell format is targeted. Virtual battery cells in self-scaled formats are considered, and its electrical properties were derived from their prototype cell as a reference using electrode stack volume as a proportionality factor and aligned with ProLogium. The scaled cell dimension is 310 x 100 x 45 mm with lateral poles, compliant to the VDA standard module and following the BEV2 standard thickness.

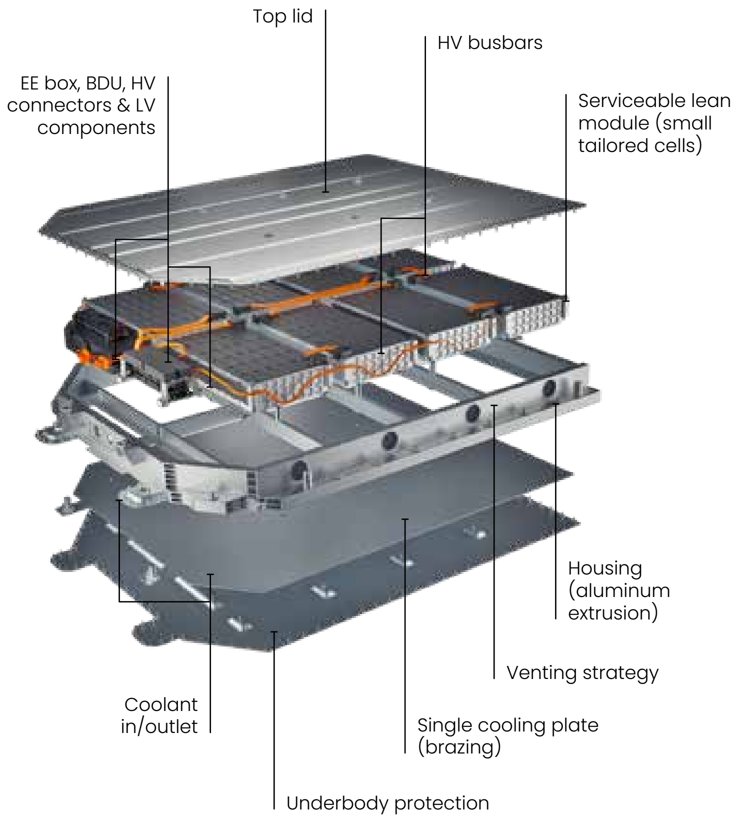
Based on swelling data over lifetime and state of charge provided by ProLogium, the distance between the cells is set accordingly. At the pack level, the design parameters determining the structural stiffness and the air clearances impacting the crash resilience are independent from the cell chemistry and therefore adopted from standard values for LIBs.

The design parameters to be considered for the housing and cross beam wall thicknesses for structural stiffness and the air clearances of the modules to the walls for safety in the event of deformation in a crash case are independent of the cell chemistry and are therefore set to the standard values. The same applies to the considered dimensions of the E/E components, the BMS and the thermal system. Overall, a concept layout with 8 cell stacks in transverse orientation offers many design advantages in terms of package structural stiffness, busbar routing, venting flow, cell stack complexity and cooling design, while maintaining a decent volumetric packaging density.

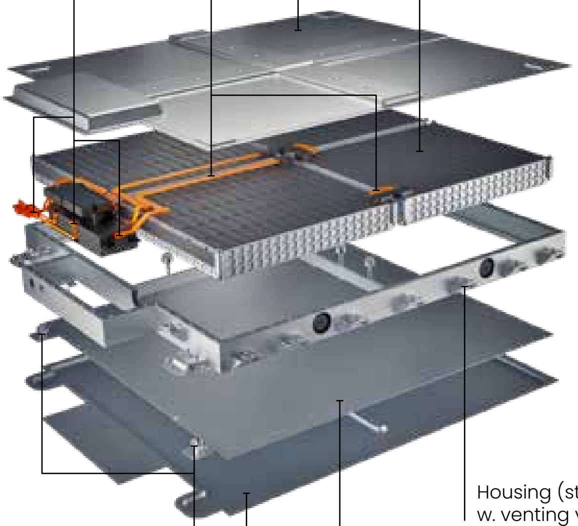
By reducing the cell stack complexity, the resulting module design achieves a structure with few components, little space requirements and low overall weight. In addition, the higher thermal safety of the SSB cells allows welding closer to the cells resulting in a leaner module with high structural integrity. The end plates are welded together with the base plate and the side walls, creating a structural cage for the pre-compressed cell stack. Openings in the busbar holders allow for unrestricted gas release in the event of thermal runaway of one cell. Any thermal event within the battery system caused by thermal runaway of a single cell is less severe compared to similarly sized standard LIB thanks to less liquid electrolyte. This reduces the overall effort required to make the battery system safe against thermal propagation (TP). With the currently applied cell pads, which also act as thermal barriers between the cells, a thermal propagation from triggered cell to neighboring cells can be prevented.

The design supports a single cooling plate approach for the pack. This not only reduces the cost, number of parts and the total weight of the battery system, but also reduces the space required for the cooling plate by eliminating any connector between the individual cooling plates. Figure 2 depicts the overall pack concept with SSB lean modules, which results in an energy density of 215 Wh/l that is in the upper range of existing batteries using conventional LIB cells but not revolutionary.

To demonstrate the potential of higher achievable energy densities, next step is to create an optimized design. This is done by scaling large custom cells and using larger but fewer cell stacks with fewer air gaps and a slimmer busbar routing. Steel is used instead of aluminum housing, which allows thinner housing walls and reduction of crossbars. Fewer TP measures with a reduction in venting paths are



2.
State of the art SSB system design



3.
Optimized SSB system design

possible thanks to the higher thermal safety. With this strategy, the height of the pack can be reduced by eleven percent. Wireless BMS slaves provide further volume savings potential. Figure 3 shows the resulting optimized pack, with a total of four major modules and a total of 96 large cells in series achieving an energy density of about 280 Wh/l with a serviceable design. Assuming the identical design is also suitable based on ProLogium's coming generation featuring a silicon oxide anode, announced for 2024, which is expected to provide a significant increase in energy density to 950 Wh/l at automotive-type cell scale, this would result in a pack level energy density of 460 Wh/l.

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Summary and outlook

SSBs offer the potential to realize the increasing driving ranges of battery electric vehicles expected for the end of the decade. The achieved energy density of the elaborated state of the art pack design is competitive by current standards, however the cell properties are not revolutionary. Nevertheless, the design was implemented because of the expected potential of solid-state cell upcoming generations.

FEV is continuously investigating new and innovative technologies to understand their key benefits and challenges. Target is to provide best-in-class technology to our customers with a deep technical understanding. Therefore, FEV aims to conduct detailed cell tests and build a prototype solid-state battery pack to evaluate the potential. Assuming that swelling remains within controllable limits, the high safety level of the cell enables a very dense packaging, so that competitive battery systems based on solid-state cells can be built. Outstanding performances can only be achieved with a fully tailored and optimized concept design.

We love technology. And we understand it deeply. This enables us to pioneer ideas and shape strategies that keep our clients, partners and our people ahead of the game.

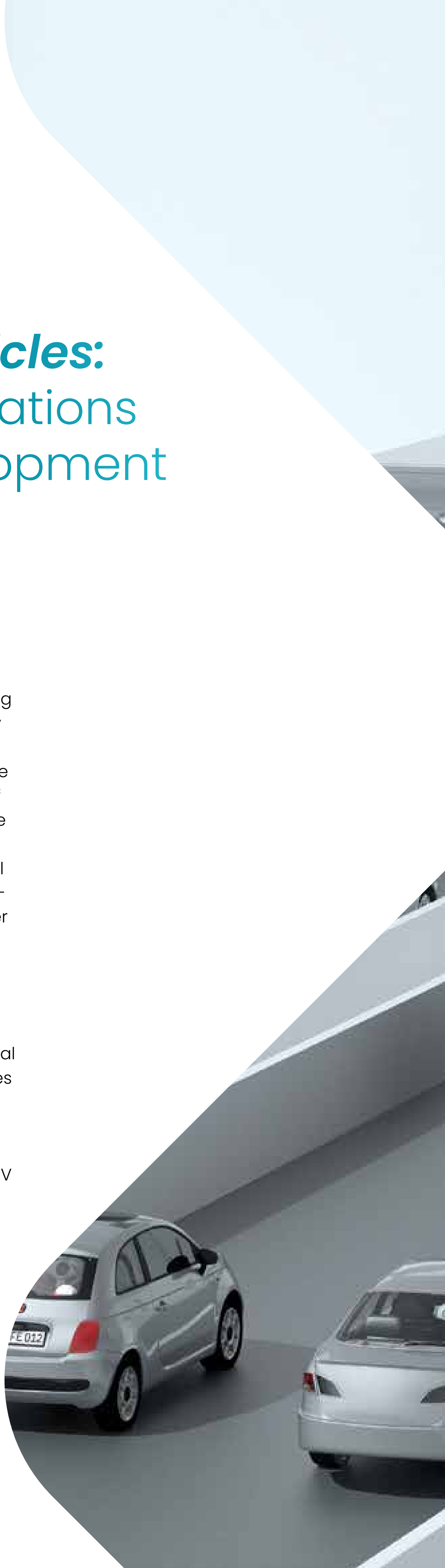
We do this by asking the right questions: Why is it this way? How can it be better? Then we explore, challenge, test and learn – continually improving the solutions we implement and the ways we work together. This helps us develop world-class innovations within sustainable mobility, energy and software to power a better future. We are so dedicated to this mission, you can feel it in everything we do.

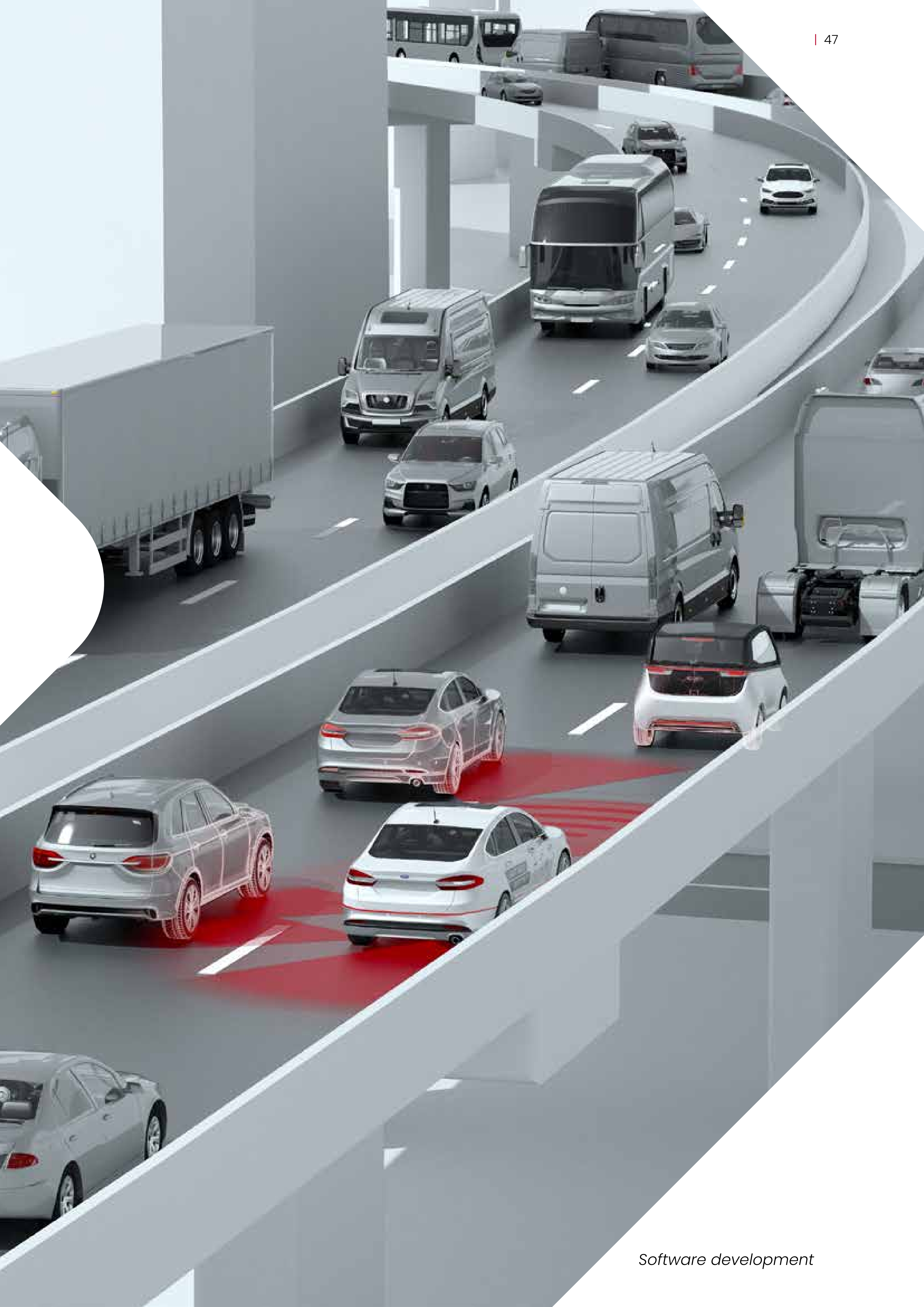
#FeelEvolution

#6
Software-defined vehicles: impact on R&D organizations and the product development process

Since its invention more than 125 years ago, the automobile is facing the biggest upheaval in its history. The challenges of climate change and technological breakthroughs are changing the rules of the game and opening new areas of business. Suddenly, the automotive industry is becoming interesting for software giants like Google, Apple or Alibaba and telecommunications companies like Huawei. By 2030, the monetization of data and the sale of new software solutions is expected to generate a revenue potential of more than 400 billion euros. The automobile will be connected to its surroundings and connectivity will play a special role in the future for highly automated driving and other mobility and service solutions. With a further increase in software content in the vehicle, new mobility features for a highly customized and enhanced driving experience can be offered.

Software-defined vehicle (SDV) describes the trend towards a vehicle that is no longer defined by its mechanical characteristics (Figure 1). A SDV is a vehicle whose features and functions are running on modern vehicle hardware but are primarily enabled by software. The software contributes significantly to the customer experience and enhancement of these vehicle features and functions. SDV reflects a complete change in development philosophy and therefore implies a fundamental change on how to develop vehicles in the future.



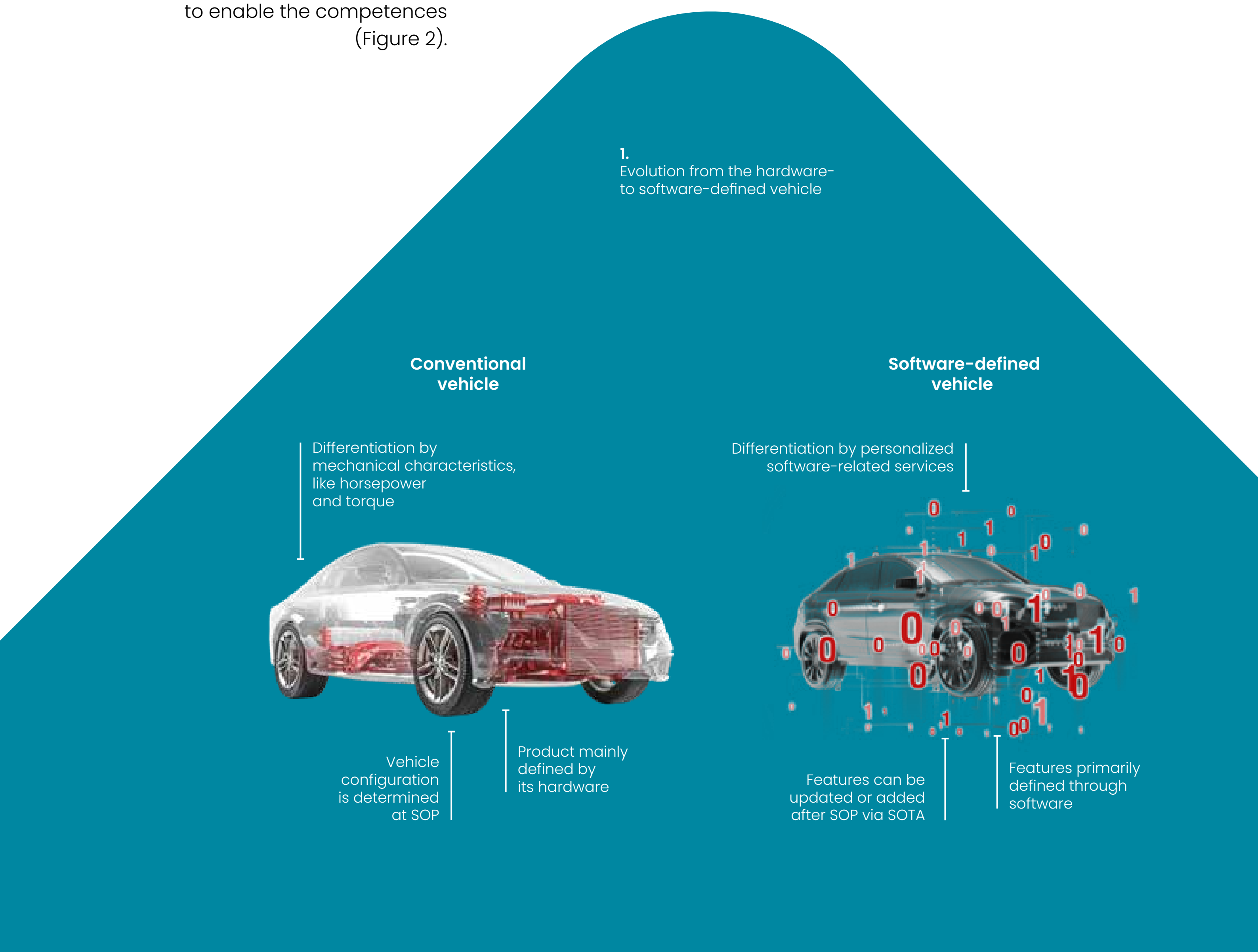


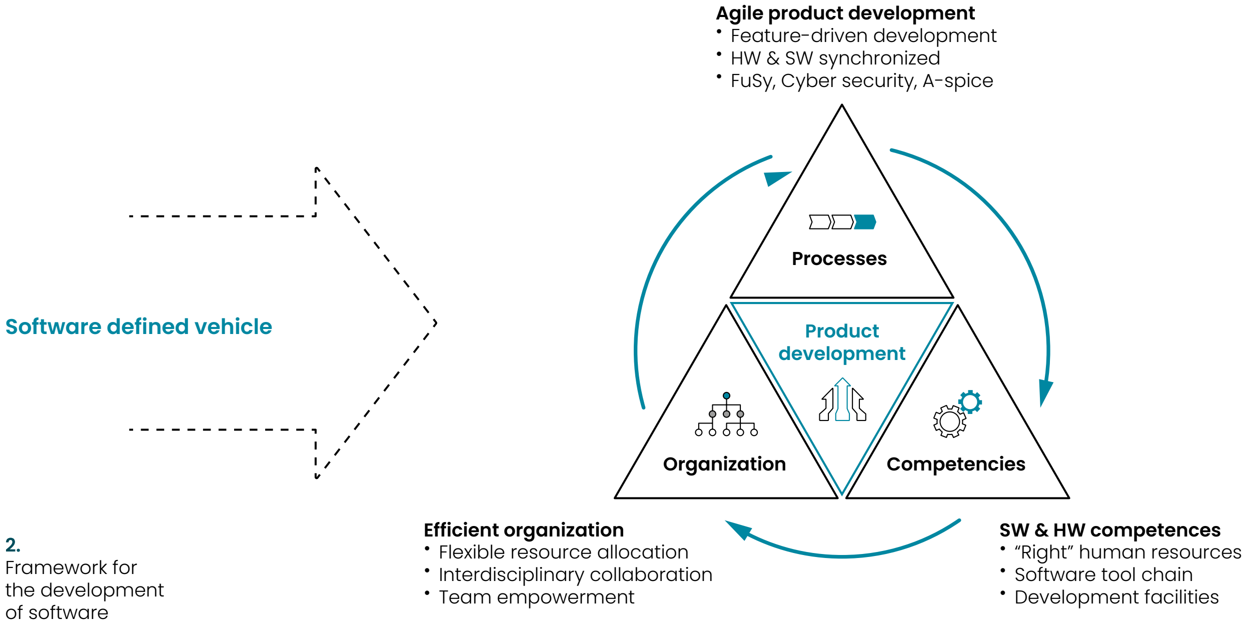
Software and hardware development are difficult to reconcile due to fundamental differences in terms of processes and organizational aspects. Traditional players in the automotive industry must ask themselves how well they are prepared for the development of software-defined vehicles. To support the automotive industry in its transformation towards the software-defined vehicle, FEV Consulting has developed a framework that covers all the dimensions of a professional R&D organization: the product itself, the product development process, the competencies to execute the processes and the organizational structure to enable the competences (Figure 2).

Decoupling of software from hardware through feature-based development

Software and hardware have traditionally been developed in very different ways. This is due, among other factors, to the different high cost of change. While revisions in software are very easy to do, changes to hardware along the development process are very cost intensive and involve long lead times. In order to bring these two worlds together, FEV Consulting has developed a concept based on the typical V-model. At the same time the principles of the function-based development is taken into account. The concept is characterized by three core aspects:

1. Maximum decoupling of hardware and software development through feature-based development
2. Reduction of the overall development timeline though extensive parallelization of tasks
3. Facilitation of post SOP development enabled by OTA update capabilities



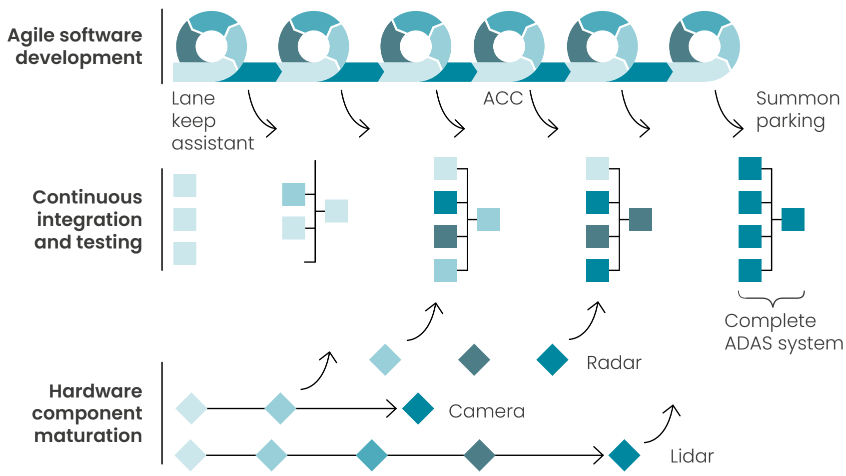


2.
Framework for the development of software defined vehicles

Most importantly, the perspective on the overall system architecture needs to be changed from component-based to feature-based. Each feature fulfills a particular set of customer requirements. Therefore, the user requirements have to be linked to the features, which then define the subsequent software and hardware requirements. After this initial requirement definition, hardware and software can theoretically be developed independently. However, the goal is to achieve an initial requirements definition that can be continuously updated throughout the development process.

For the success of a vehicle development project, it is crucial to closely monitor whether the developed products meet the defined requirements and to regularly challenge and, if necessary, update the requirements. To enable early testing of software, hardware systems must be made available for testing earlier in the process. For this purpose, e.g., previous generation hardware or early prototypes can be used as a substitute until final harware is available. Rapid prototyping methods and simulation of hardware components further support the process.

3.
Feature-based product development scheme



New competencies to manage and control software development processes

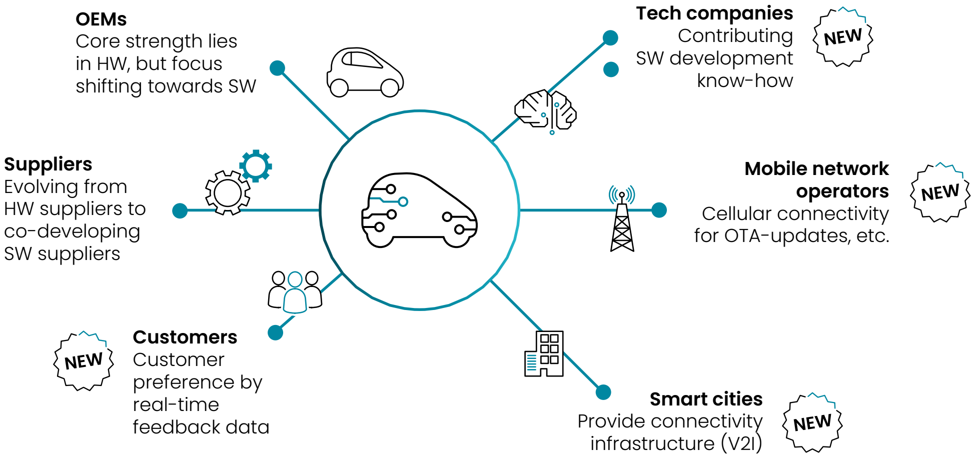
Software development requires a whole set of new capabilities: high-performance computing, cloud and over-the-air technology, software architecture development, software design and coding, software testing and virtual vehicle development are only a few of the new product and development competencies required. On top, process know-how needs to be built up to successfully apply (model-based) systems engineering, agile development methods, and portfolio planning. Given the scarcity of available methods talent and resources in the market, it is very difficult for OEMs to build up the competencies alone. The right mix of in-house capabilities and partnering with other automotive or non-automotive players is a key success factor to get an early stake in the market. An elementary step is to define which technologies and software features are strategically important and should be prioritized for building up in-house capabilities.

The OEMs' attempt to capitalize on digital innovation, combined with exploding system complexity and an unmet need for software experts, is drastically changing their vision of the automotive value chain. Automakers are strengthening their software development and integration capabilities to allay fears of being reduced to a low-margin hardware provider. Still, the biggest challenge is building up the required capabilities. Their software expertise traditionally focuses on developing vehicle applications in selected domains such as powertrain and ADAS. Software-defined vehicles however require an end-to-end software and hardware platform, including a strong cloud backend. Simply increasing resources will not lead to success, as availability of required talents in the market is scarce.

To maximize the value proposition across the entire digital car stack auotmotive OEMs must consider new, more diverse collaboration models that go beyond purely vertical and established customer-supplier relationships (Figure 4).

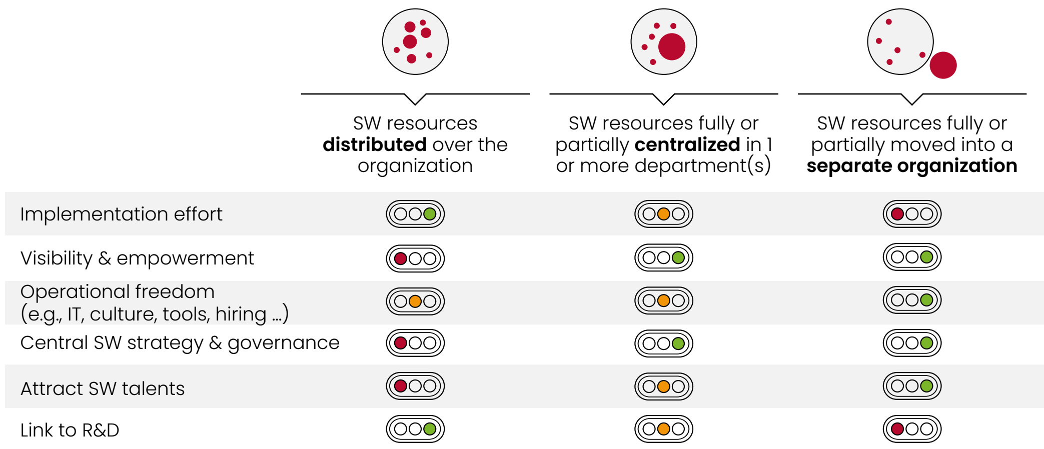
Software must be part of the overall organizational strategy

One of the biggest challenges that traditional OEMs face in terms of software-defined vehicle development is the existing hardware-oriented organization. OEMs are organized according to traditional development processes, including clearly defined responsibilities and hierarchical structures for hardware systems. This environment does not foresee the seamless integration of efficiently developed and continuously integrated software. Pure software companies follow a different development flow with decentralized responsibilities in agile teams, flat hierarchies and exchange of know-how in distinct competence centers. For traditional automotive industry players, this is not only a change in processes, but a radical change in corporate culture. In the past, traditional OEMs were strong in hardware development, thus hardware was always prioritized over software. This mindset is also reflected in classic organi-



4.
New automotive ecosystem

zational structures, where software responsibilities are distributed across the organization with different departments working on their own software. With software becoming increasingly complex in the whole vehicle, an standardization and centralization of certain software features becomes increasingly important. Many OEMs have already acknowledged this by reorganizing their software development departments towards a more centralized approach. While each specific case must be evaluated individually, centralization of software competencies – in-house or in a separate spin-off offers several advantages over competency distribution across the organization (Figure 5).



5.
Software integration into organizational structure

Organizational change must be done right

The trend of software-defined vehicles is a chance, as it comes along with new revenue potentials and opportunities to further enhance the product offering to the customer. However, organizational excellence is needed in all dimensions of a professional R&D organization to develop SDVs. To successfully manage the transition, full management commitment for the complete process and the willingness to tackle key roadblocks is crucial. In terms of processes, the key success factor is to create a framework in which software development teams have enough freedom to work in a very agile and flexible way while still meeting the required vehicle development milestones. The right mixture the right mixture of in-house capabilities and partnering with other automotive or non-automotive players is needed to get an early foot into the market. The organizational structure must create the right boundaries to not only acknowledge the importance of software and a different development mindset within the organization, but also balance the interests of different stakeholders. An agile development environment with cross-functional feature teams is the baseline for releasing software features at a high frequency.

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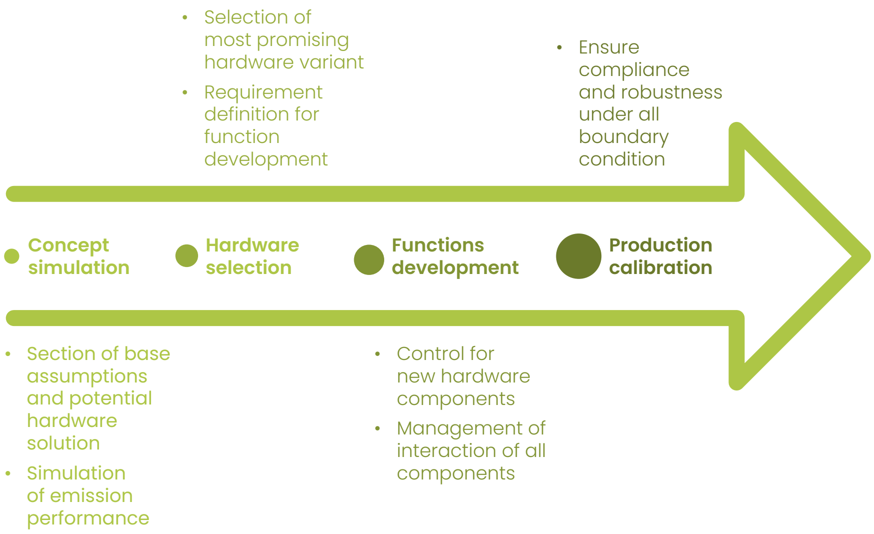
EURO 7

#7
FEV’s advanced hardware, controls and calibration solution for ***EURO 7***

The introduction of the upcoming EURO 7 emissions legislation is targeting ultra-low emissions under all operating conditions. This is realized by introducing very strict emission limits, much wider boundary conditions but also by introducing limits for emission species like N_2O which have not been limited so far.

On top of the quantitative and qualitative intensification of the emission limits also the in-use compliance will be tightened. The limits will apply to most driving scenarios and will be monitored online within the vehicle which will require a new diagnostic approach called OBM (On-Board Monitoring).

To comply with the new limits and to ensure the required robustness new hardware components and controls will be required. To tackle those requirements FEV offers a holistic approach (Figure 1). Starting with a concept simulation the most promising hardware can be selected and potential robustness risks identified. Using FEV's long-term experience in function development new controls logics can be tailored to the new hardware. Due to FEV's collaboration with different hardware suppliers such as HJS Emission Technology an early physical demonstration of the impact of the hardware and software solutions can be realized. The result is a powerful combination of hardware and controls logic allowing a robust and efficient calibration for production.



1.
FEV's holistic product development approach

Concept simulation

The development of state-of-the-art powertrains for EURO 7 requires specific, targeted development methods. FEV has developed extensive patented and patent-pending development methods in the field of simulation as well as testing and aging of emission-relevant components, which make it possible to demonstrate high robustness and forecast accuracy at an early stage of development. The key points of these development methods are explained in the following. Figure 2 gives an overview of the simulation-focused optimization method that is used for the concept development.

Emission simulation is an essential pillar in the frontloading of development. Both the sub-models and their parameterization are continuously refined, while the real-time capability enables their use within the framework of virtual calibration by means of hardware-in-the-loop.

To simulate a wide variety of powertrains in various drive cycles and real driving scenarios, a modular simulation model construction kit can be used in the GT-Suite® software environment. It can be used to model variations of the powertrain and operating strategies at different levels of detail. The engine raw emissions are modeled based on stationary and transient measurement data from engine and roller chassis

2.
Simulative optimization method to achieve emission compliance

test benches. This is done under standardized boundary conditions, i.e., at low and warm coolant and oil temperatures and optimized combustion parameters.

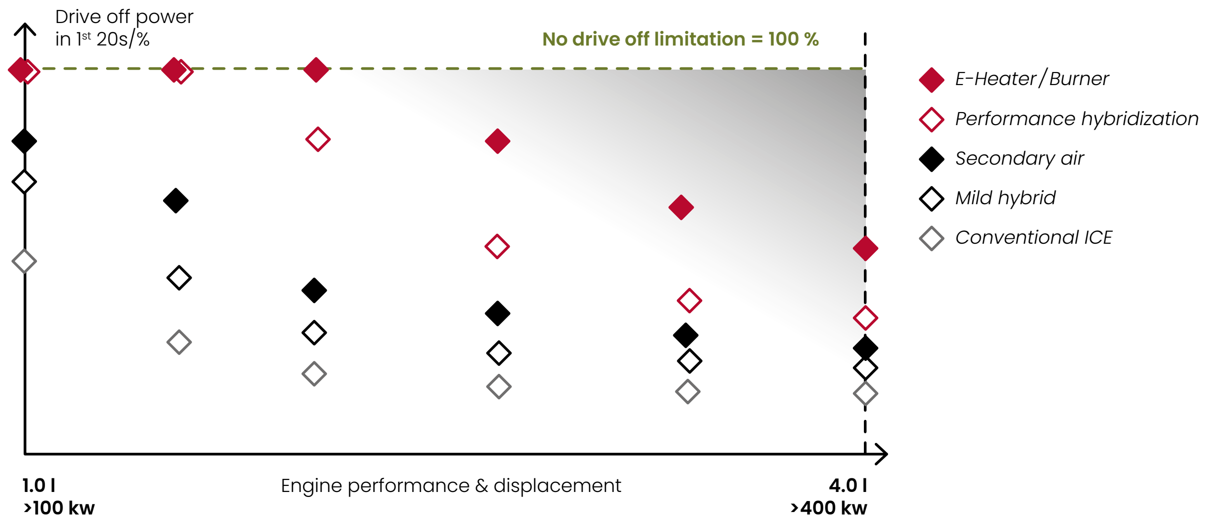
The simulation model for the exhaust aftertreatment is based on a map-based approach. An equidistant discretization of the coated monolith allows a mapping of the warm-up behavior along its longitudinal axis to consider individual, temperature-dependent conversion rates.

The main influencing factors for the resulting conversion efficiencies for a given catalyst formulation are the space velocities (SV), the temperature (T) of the respective discretized partial volume, the rel. air/fuel-ratio (λ) in the exhaust gas and the amount of stored oxygen for three-way catalysts. An accurate representation of the warm-up behavior of the exhaust aftertreatment and a derivation of the effect on the pollutant conversion are particularly important for the determination of tailpipe emissions. Particularly during the catalyst heating phase and the first load requirement during this time, strong temperature gradients in the catalyst and thus a significant change in the conversion of raw emissions can be observed. Only the active part of the catalyst is effective in pollutant conversion. This effect increases the effective space velocity during the cold start phase and the conversion efficiencies are correspondingly low.

The model is physical-empirical and based on measurement data of the corresponding catalytic converter.

An essential part of a precise emission simulation is the correct modeling of the exhaust aftertreatment components. During the development of the RDE emission simulation methodology, it was identified that initially three-way catalysts could rarely be modeled with sufficient precision. The reason for this lies in the mostly limited measurement data available from catalyst manufacturers and OEMs. For a precise prediction of the emissions under RDE boundary conditions, knowledge of the conversion rate at highest space velocities and in a wide temperature range is of interest. As a result, FEV developed a dedicated testbench can be used to characterize catalysts under exactly those conditions.

»Due to FEV's collaboration with numerous different hardware suppliers, an early demonstration of hardware and software solutions can be realized.«



3.
Impact on drive-off power limitation depending on engine size and technology package for a gasoline mid-sized SUV

Technology updates for EURO 7

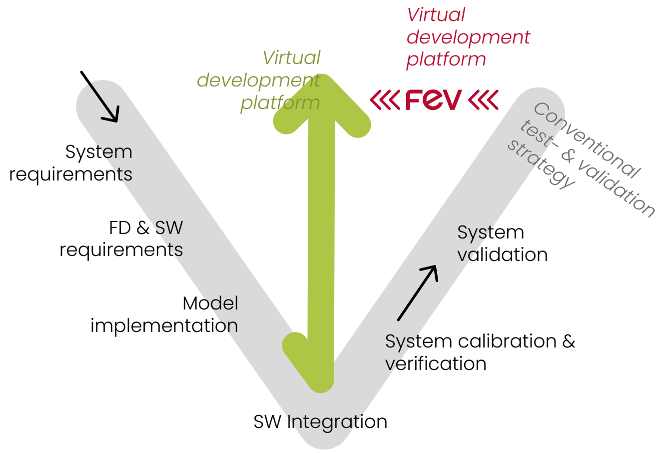
Although the exact boundary conditions for EURO 7 still have to be defined, a group of technology updates can already be assumed today. EURO 7 will drive much more aggressive cold start requirements on one hand and a significant extension of the operation range with binding legislative limits on the other hand. While the latter can be addressed by increased catalyst volumes and optimized combustion parameters including Lambda = 1 for gasoline engines in the whole engine map, the cold start requirement will drive a combination of new hardware as well as controls. Regarding hardware a device for rapid heat-up will be required. This can be realized by an electrically heated catalyst operated at 48V or an exhaust burner. On the part of controls, a certain torque limitation or an electric drive-off (Hybrid Electric Vehicles, HEV) should be considered. The control strategy is strongly depending on the installed hardware and application. The qualitative result of a concept study for a mid-size SUV with gasoline powertrain and different technology packages is shown in Figure 3. While for small and medium sized engines an electrically heated catalyst and strong hybridization can avoid any performance loss, conventional engines without or with little hybridization will suffer from significant power imitations in the initial cold start phase.

Function development and calibration

The aggressive extremely high emission robustness requirements expected for EURO 7 are driving – a side from more powerful hardware – more complex software and calibration solutions.

Figure 4 shows FEV's function development process to achieve a robust EURO 7 application. Starting with the system requirements as defined in the concept, the requirements are specified for each function and the entire software in a V-cycle approach. Respecting the increased robustness requirements and the general trend for shorter development cycles, the right path of the V-cycle is using extensive virtualization including advanced Hardware-in-the-Loop (HiL) simulation.

4.
FEV's function development process for EURO7



Functions Development

- Function development starts in parallel to concept evaluations and heavily relies on virtual test platforms:
  - Functions are tested in relevant EU7 conditions before first prototypes are available
  - Functions are continuously tested in all relevant EU7 conditions in the virtual development platform

› *Increased maturity and reduced development time and effort compare to conventional test & validations strategies*

As a specific example for this process this paper article will now demonstrate the software development to operate an electrically heated catalyst EHC. Once the hardware of the engine and the after-treatment system are defined, the controls logic must adapt accordingly. For this the control of new devices must be addressed on one hand, while the interaction of the overall system needs consideration on the other hand.

FEV has developed a modular powertrain control function library. The basis of this library is a consistent software architecture that groups functions according to physical interfaces and a development framework that supports function and software development from prototype to series production.

The library is continuously extended based on new requirements and technologies that are introduced for EURO 7. The functions are mostly model based to achieve ultra-low emissions under all operating conditions. The ideal interaction between different sub-systems is ensured by smart system coordinators. Figure 5 shows the core functionalities of an electric heated catalyst as an example of such a library function.

The development of these functions starts ideally in parallel to the concept simulation. The concept simulation environment is used as a virtual test and calibration platform before the first prototype is available. Furthermore, it and to reduces the test and calibration effort with test vehicles in later development phases.

The development framework facilitates a deployment of the functions on either rapid-prototyping or the final target control unit, depending on the development stage.

Performance during on road tests

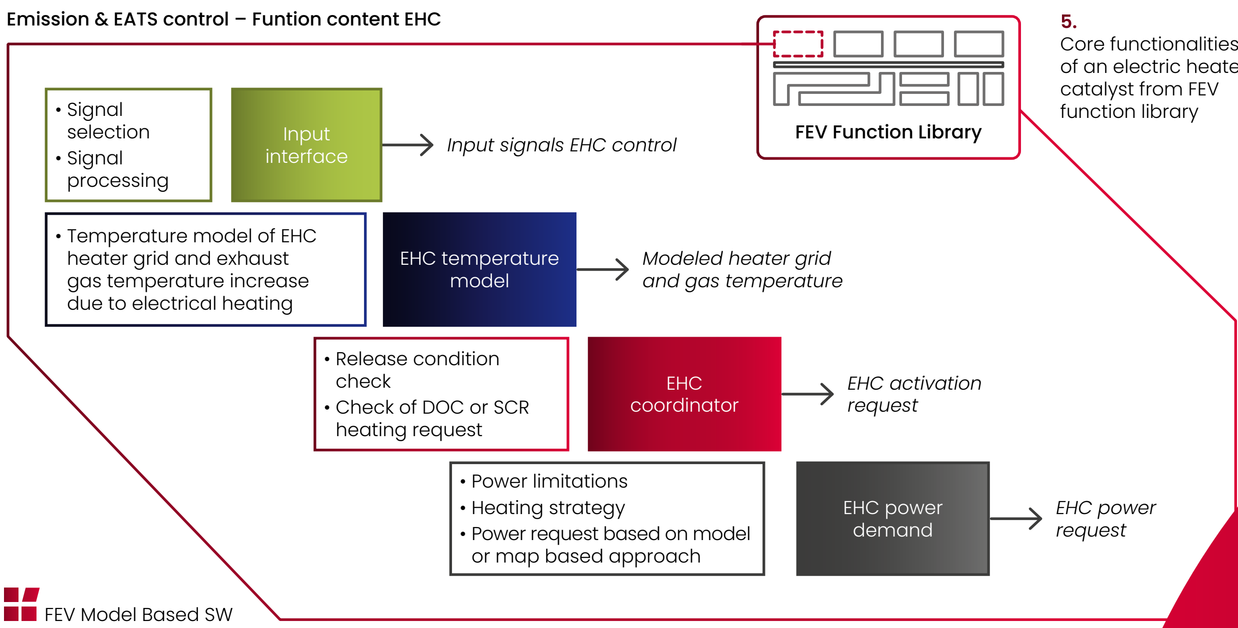
Following the calibration of the software functions, the potential of the newly developed exhaust system was to be determined in road tests. For this purpose, a newly designed exhaust system was installed into the FEV Heavy Duty Demonstrator Vehicle.

The new control software was deployed to a rapid-prototyping control unit that was used in parallel to the engine control system. Specially developed software interfaces have been used to feed required input variables from various sources to the controller or to control individual actuators such as the AdBlue dosing valves. The exhaust aftertreatment system was provided by HJS Emission Technology. A 10 kW EHC (HJS eHeater) and the DOC (Diesel Oxidation Catalyst) are mounted close coupled at the turbine exit, whilst the first SCR/ccSCR (Selective Catalytic Reduction Catalyst, close-coupled SCR) followed by a DPF (Diesel Particulate Filter) and a second SCR are located in the aftertreatment box.

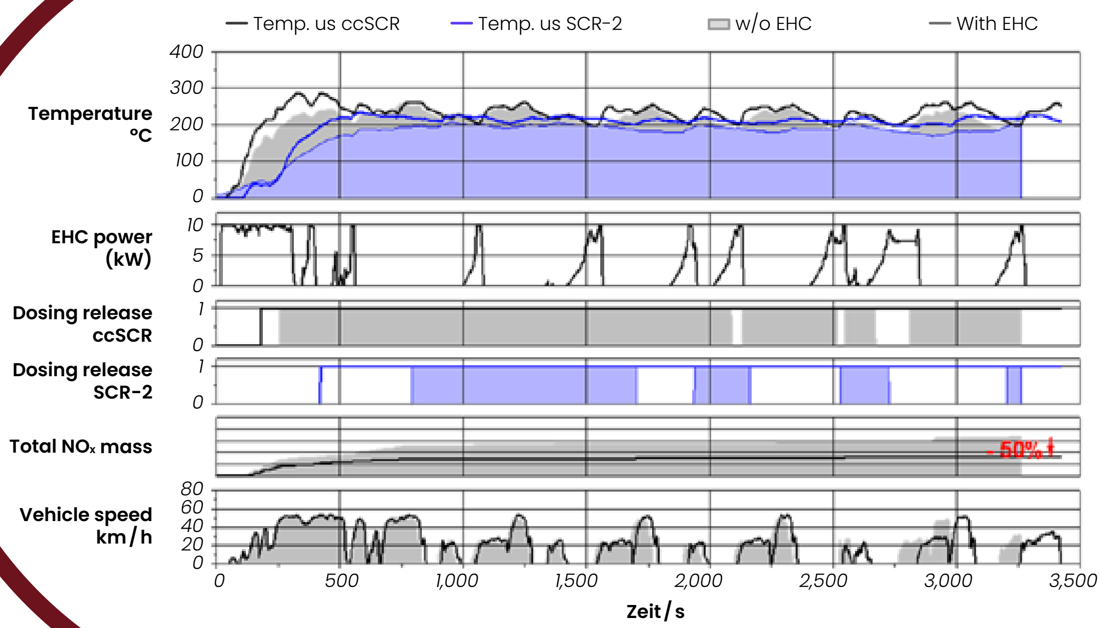
Various tests have been performed. As an example, an urban delivery cycle is displayed here. This test begins with a 15-minute drive in an inner-city area. This is followed by a total of nine simulated delivery stops (three times, 1, 2 or 3 minutes each). During these stops, the engine continues to idle. Between the stops, short runs of varying duration of approx. 1 to 4 minutes follow. The special focus for this type of test, in addition to the warm-up phase after the cold start, is on the potential cooling of the exhaust system during the stop phases.

For better comparability and to define a worst-case, all tests were started with the engine cold and the NH3 storage on the SCR systems empty. The aim of the tests was to demonstrate the performance of the new exhaust aftertreatment system, in particular the benefit to be achieved by the EHC. For this reason, all tests were run twice, once each with active and non-active EHC. Figure 6 shows a comparison of the results for the two tests run.

There is a direct activation of the EHC after engine start and the resulting increases in the temperature level upstream of the two SCR components of up to 60°C. For these tests, this results in an earlier start of dosing of about 77 seconds for the first AdBlue® dosing valve and about 370 seconds for the second dosing valve.



5.
Core functionalities of an electric heated catalyst from FEV function library



6.
Results of urban delivery tests with and without EHC

The stop phases lead to cooling out of the exhaust system. In a system without EHC, this leads to a loss of dosing release for a conventionally arranged SCR over a long period of the test. But even an SCR located close to the engine cannot be continuously supplied with reducing agent under these conditions. As a result, further NOx breakthroughs are seen at tailpipe. In the test with EHC active, the EHC is reactivated when the temperature drops below a pre-calibrated threshold and prevents the temperature from dropping too much. The dosing on both AdBlue valves remains active during the entire test period.

In this way, a reduction in NOx emissions of about 50% can be achieved for the entire test. This compares with an input of electrical energy of about 2.19 kWh, of which about 0.9 kWh is used during the cold start phase in the first 600 seconds.

TEXT

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Summary

The holistic FEV approach for EURO 7 starting with advanced concept simulation ramping into dedicated function development and calibration delivers an excellent ideal foundation for the achievement of the future EURO 7 legislation.

We not only show you how it looks, we explain why!

feel evolution

#8
FEV Zero CO_2 ***Mobility Conference*** 2022

Electric cars make positive contribution

The international FEV conference "Zero CO_2 Mobility" at the end of 2022 was once again attended by high caliber of experts. Participants agreed that the 1.5-degree target of the Paris climate protection agreement in the transport sector can no longer be achieved with the measures introduced to date. Consequently, further tightened regulations for the phase-out of fossil fuels up to a ban on fossil fuels were discussed. At the same time, the experts in Aachen pleaded for the parallel pursuit and promotion of all technological alternatives from renewable energy sources for sustainable mobility – from e-vehicles to the use of green hydrogen in fuel cells and combustion engines to e-fuels for the existing fleet.

An online survey reflected the conviction of the more than 100 participating experts: 93 percent said that global warming will exceed +1.5 degrees by 2050, and a third of them even said it will be more than +2.5 degrees. This shows how important it is to finally push maximum speed ahead for the fastest possible transition away from all fossil fuels in the transportation sector.

In his welcoming address, host Dr. Norbert W. Alt, COO of FEV Group, assessed the development of electromobility worldwide as positive, with more e-cars now being sold in Germany than new cars with diesel engines. However, he said, the associated CO_2 reduction will not be significantly noticeable until 2040 and beyond due to the global existing fleet of around 1.4 billion passenger cars and light commercial vehicles. For this reason, he said, it is important to pursue all technological solutions such as hydrogen in fuel cells as well as in internal combustion engines and additionally large quantities of sustainable fuels for the existing fleet immediately and in parallel, in addition to electromobility. In this context, the frequent discussions about efficiency in the generation of non-fossil energy sources are misleading. According to this, the world does not have an energy problem, since only about 60 minutes of solar energy reaching the earth's surface is sufficient to meet the entire global annual energy demand.

Focus on hydrogen

On the path to defossilization, green hydrogen is rated as the key potential energy carrier of the future. The EU recently released 5.2 billion euros to support a total of 35 hydrogen projects, flanked by another seven billion from private investment sources. In Aachen, the focus was on the current challenges in dealing with hydrogen, gaseous or liquid, on climate-neutral production, transport, storage, distribution, and infrastructure. Due to the high efficiency and ranges with short refueling times, especially heavy-duty commercial vehicles in long-distance traffic, various off-road applications, railroads and finally aviation rely on hydrogen and fuel cell drives.

In very concrete terms, Linde Engineering presented its three main objectives in the handling and transport of liquid hydrogen: reducing the dead weight of distribution systems and transport equipment using aluminum or composites, improving the value chain through shorter refueling times of transport equipment and fewer losses through highly efficient pumping systems.

As one of the world's leading e-fuels producers, HIF Global also reported on the commissioning of its site in Patagonia, Chile. There, green energy from a wind turbine and recycled CO_2 will be used to produce green hydrogen and process it with

Zero CO_2 Mobility

Here more info on the topic!

maximum efficiency into e-methanol, e-fuels, and other synthetic fuels. The company plans to have delivery capacities of 750,000 liters of e-methanol annually from 2023, more than 55 million liters of e-fuels from 2026, and more than 550 million liters of e-fuels from 2028. HIF Global aims to further decarbonize the transportation and mobility sector and significantly accelerate the hydrogen economy in a sustainable, competitive, and safe manner.

Regarding the wind turbine, Audi assumes an overall efficiency of 74 percent and thus almost the same value as for the generation of fossil gasoline.

Electric mobility continues to gain ground

Clear signals for technological change are also coming from e-mobility. The global availability of BEVs (Battery Electric Vehicles) has increased significantly, the extremely high efficiency of the electric drive is unrivaled and is therefore assessed as the main drive technology of the future to be used in passenger cars and increasingly also for truck applications. This is also reflected in the willingness and success of car manufacturers to consistently electrify their own icons: In Aachen, Volkswagen traced the path from the legendary cult object Vee-Dub to the all-electric ID.Buzz, which, as part of the decarbonization program, is the first CO_2 neutral Volkswagen produced and will be handed over to customers without the much-cited CO_2 backpack.

At the FEV conference, Indian manufacturer Mahindra outlined the political levers on its home market: targeted government support, such as for local battery and component production or the development of infrastructure, the stringent definition of national standards and concrete incentives for Indian OEMs are intended to achieve the transformation of mobility, which manifests itself, among other things, in the sales target of 10 million electric vehicles in India in 2030.

The Zero CO_2 Mobility Conference 2022 also reported on the further accelerated planned expansion of the charging infrastructure for BEVs, particularly in HPC chargers for long-distance mobility.

Solid-state batteries for more sustainability

Solid-state batteries are also helping to accelerate the global availability of e-mobility, and they can score with tangible advantages compared to lithium-ion batteries: FEV partner ProLogium presented its latest product generation in Aachen, which features up to 79 percent higher energy density with 66 percent faster charging time and 16 percent lower costs compared to conventional lithium-ion technology. In addition, the used solid-state electrolyte is 90 percent recyclable as well as reusable, and the intrinsic safety of the batteries against thermal runaway has also been significantly increased.

FEV, as a partner company of ProLogium, has many years of experience in battery development. The customized design and integration of battery systems consider the battery management system as well as the cells, modules, and packs. Depending on the application, the company offers solutions with high specific power and energy density. With the eDLP near Leipzig, FEV operates the world's largest independent battery development and test center for high-voltage batteries.

It won't work without phasing out fossil fuels

Despite the impressive technological progress, the targeted climate goal for 2050 cannot be achieved unless stricter targets for reducing energy consumption and CO_2 emissions are implemented as quickly as possible, concluded numerous contributions as well as the exciting panel discussion at this year's FEV conference. The following options were discussed at this expert conference:

- CO_2 taxation models in the transport sector up to extreme values of 1,000 euros per metric ton of CO_2 (this would correspond to a CO_2 tax of 2.56 euros per liter of diesel fuel alone) to accelerate the technology shift away from fossil combustion engines
- Significantly higher RFNBO (Renewable Fuels of Non-Biological Origin) quotas for the use of e-fuels in existing fleets; the current target here is only around 5.5 percent in the EU in 2030

- A complete phase-out of fossil gasoline and diesel in 2040 was also discussed, like the coal phase-out in Germany. Thus, all vehicles would run either electrically, on hydrogen, or on H_2 based e-fuel and partially on biofuels, including existing fleets.
- In addition, speed limits for freeway traffic can also contribute to CO_2 reduction in the transport sector with immediate effect: one to two percent at 130 km/h in Germany, even four percent at 100 km/h as in the Netherlands.

A "business as usual" is by no means any option. Only all mentioned measures on aggregate can provide a way out of fossil fuels and towards achieving the 2050 climate targets in the transport sector. However, only if this is done immediately and in addition to the technological shift towards electromobility and hydrogen-based energy sources that has already begun.

It has been positively assessed that almost all automakers are pushing e-mobility forward with great energy. Nevertheless, it is important on the part of the legislator to create appropriate boundary conditions that make driving with fossil fuels unattractive. Mobility must be converted to regenerative electricity and regenerative H_2 based energy sources as quickly as possible. A significant CO_2 tax would be the right impulse from Brussels (place of European Parliament). The currently planned regulation of 5.5 percent RFNBOs fuel blending for existing fleets by 2030 and 100 percent e-vehicles by 2035 is not sufficient for the climate targets.

Visit us at the seventh international Zero CO_2 Mobility Conference, which will take place this year as a special edition on 7-8 November in Berlin.

2022
Impressions

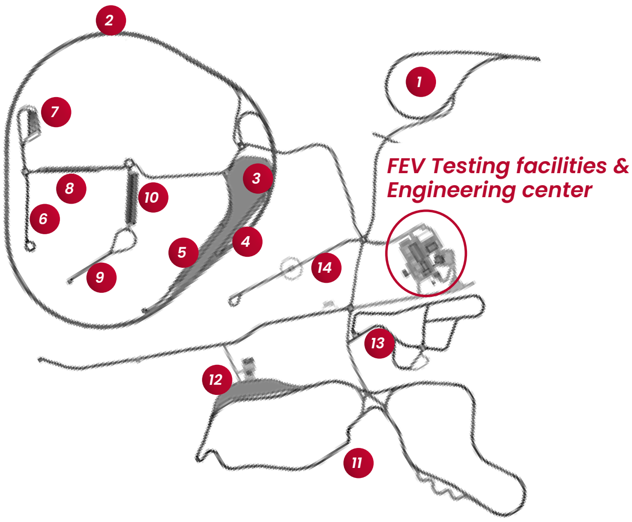
#9
FEV and UTAC open ***first development and test center*** in Africa

Premiere on the African continent: FEV, together with joint venture partner UTAC, has commissioned Africa's first test center in Oued Zem, Morocco, some 150 kilometers southeast of Casablanca. As an innovation leader, FEV thus offers its customers highly attractive conditions for vehicle development and testing almost all year round.

The launch of the first test center on African soil is an important strategic milestone for FEV. The company has already been expanding its presence in Morocco since 2018 and can now offer its customers a unique package of state-of-the-art development, testing and homologa-tion services right at the gates of Europe.

The state-of-the-art Oued Zem facility is located at an altitude of 850 meters in Morocco's Atlas foothills. The site covers a total area of 500 hectares and includes an extensive, newly built test track for passenger cars and commercial vehicles. It enables a large number of test drives on a total of 14 sections and individual routes. The centerpiece is a 4-kilometer straight-line coast down

1 Coast down (4 km long)
2 High speed track
3 Dynamic platform #1
4 Dry braking
5 Wet braking / Low grip track
6 Dirt track
7 Sloped tracks
8 Acoustic test track
9 Degraded road
10 Special tracks (undulated track, acoustic tunnel, gravelled track, ford crossing, bumps, cobbled track)
11 Road circuit
12 Dynamic platform #2
13 Urban track
14 ISO 10844 acoustic track



»The site, which covers approximately 500 hectares, includes a completely new test area for passenger cars and commercial vehicles, which allows a wide variety of test drives on a total of 14 sections and individual tracks.«

track (according to EU and Japan ISO 17025:-2022-07 regulations), which is unique in the world under those favourable conditions. Test sections for high-speed driving, active safety, dry and wet braking, and acoustic tests as well as dirt, sloped, and paved tracks, an ISO 10844 acoustic track, city tracks, off-road tracks and further tracks complete the portfolio. The warm and dry climate of Oued Zem allows almost year-round test operation. The new location is also an ideal starting point for long-distance driving in the Atlas Mountains, which are only 70 kilometers away.

In the connected test center, which is also newly built, customers will find a complete range of test benches for powertrain development (electric, hybrid and combustion engine vehicles), RDE cycles, endurance and reliability testing, dynamics, acoustics, and climate testing. In addition, the modern complex houses spacious offices, conference and seminar rooms, and presentation areas.

A total of four halls with separate entrances, office and workshop areas for vehicle preparation are available for customer vehicles. A nearby located hotel with restaurants, spa and leisure options exclusively built for guests of the test center rounds off the facilities.

From the port in Casablanca, it is only an hour and a half drive to Oued Zem. On demand, FEV is also happy to take care of the entire test handling, including pickup and return logistics of customer vehicles. In addition, the area is an ideal setting for events such as vehicle presentations, driver training sessions or internal training courses.

With the opening of the new development and test center, FEV is expanding its position as a key partner of leading companies in the transportation industry in Morocco, which includes manufacturers, suppliers, and test laboratories, as well as schools and universities.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