SPECTRUM

SUSTAINABLE MOBILITY THOUGHT AHEAD

Hybrid-BEV platform

Fuel cell freeze start

Fuel cell compressor design

Defossilization

BEV power storage

FEV Energy

Dear Readers,

For more than 40 years, FEV has stood for pioneering developments that have contributed to sustainable, safe and comfortable mobility. Currently, the automotive transformation and the challenges it poses for our customers are greater than ever. We are inspired by this change and at the same time it represents another opportunity to support our customers as a reliable partner with innovative solutions. In this issue of SPECTRUM, we would like to present you a current selection.

For example, we present Hybrid-BEV, a native BEV platform, which integrates an internal combustion engine as a highly efficient energy conversion system, giving the driving experience of a BEV while achieving the range of current diesel vehicles with extremely low emissions. At the same time, the single-platform strategy offers enormous savings potential for manufacturers as they transition to pure electric mobility based on a BEV. In another article, we look at how electric vehicles based on fuel cells can become a genuine alternative to combustion engines or battery-electric drives. One important prerequisite for this is, among other things, that their operation in extreme subzero temperatures must be improved. FEV has investigated how a cold start can best be achieved without impairing the operation or service life of a fuel cell.

If fuel cells are to deliver high power, turbocharging makes a lot of sense. However, since there is a wide range of applications and only limited quantities are expected in the near future, the development of customized compressors will be expensive. On the following pages, we present our solution with a holistic simulation process that reduces costs and optimizes efficiency.

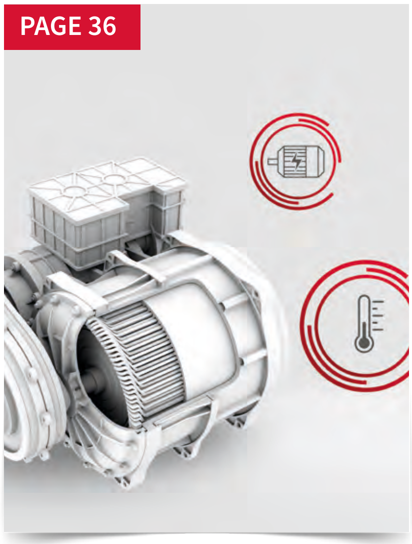
In another article in this issue, we also show the enormous potential offered by hydrogen in internal combustion engines and which exhaust gas aftertreatment systems for nitrogen oxide are useful here. We also look at new approaches for better battery performance in e-mobility and present a new thermal management approach for the most common e-motor topologies. This can reduce energy consumption significantly without much effort - and the potential is even higher for future generations of e-motors.

I wish you an exciting read.

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

Hybrid-BEV platform

Fuel cell freeze start



E-motor power saving strategy

01 TECHNICAL DEVELOPMENT MADE BY FEV

02 NEWS

HYBRID-BEV PLATFORM

MORE FLEXIBILITY WITH HYBRID-BEV

While the European market is increasingly focusing on pure electromobility, China is experiencing a revival of hybrid technology with its range advantages: China's currently best-selling so-called NEV- (New Energy Vehicle) SUV has a 40 kWh battery and an internal combustion engine as an energy conversion system in a serial hybrid configuration. The NEV category includes purely battery-electric cars as well as those with fuel cells, plug-in and serial hybrid vehicles. Automobile manufacturers thus face a particular challenge, because the parallel development of both a native BEV (Battery Electric Vehicle) and a classic internal combustion engine platform for different market needs significantly increases development costs.

The discussion about climate change impacted by CO_2 emissions is affecting all major industries including the automotive and transportation sector. Public perception of the automobile as well as legislation is now focusing on vehicles with environmentally sustainable powertrains. By 2030, the legislation for Europe for example envisages a 37.5 percent reduction in CO_2 emissions (compared to 2021) from new passenger car fleets placed on the market. And even higher emission reduction targets with values towards minus 55 percent are forecasted as part of the European Commission's Green Deal. It aims to achieve net-zero greenhouse gas (GHG) emissions by 2050. All this is expected to increase the number of electrified powertrains significantly within the next decade, since that is the major contributor to reducing CO_2 emissions in the whole transport sector.

Why two platforms?

To comply with the 2030 EU CO_2 emission legislation and to avoid penalties, carmakers anticipate a significant share of vehicles with electric hybridized powertrains (xHEV) and battery electric vehicles (BEV). OEMs have adapted their model range accordingly and currently apply a two-platform strategy within one vehicle segment to optimize the benefits of each powertrain. It usually contains a newer, pure BEV platform and a more traditional, native ICE (Internal Combustion Engine) platform for the conventional powertrain and its hybrid variants.

The sales forecast of passenger cars however still shows a significant variance in pure battery electric vehicles in 2030. It ranges from 15 to 40 percent between the main markets EU, the USA and China. Since the demand for ICE-only vehicles is likely to decline, automakers will need to respond flexibly in the future to varying call-off numbers of BEVs on the one hand and xHEVs on the other. This is more difficult with a two-platform strategy.

In view of these conditions, a better approach can be a single platform solution towards powertrain electrification, especially for "smaller" OEMs. FEV suggests creating a BEV native platform, where a highly efficient energy conversion system can be integrated, which has the feel and image of a BEV but the range of current Diesel vehicles. Such a concept would be viable when full flexibility could be achieved with a one platform strategy for BEV and xHEV – and without significantly compromising either one. Another prerequisite is that the (BEV native) serial Hybrid has no significant drawback in CO_2 compared to a hybrid solution that still connects the ICE to the wheels.

This is the subject of a FEV study that focusses on a D/E-segment SUV (mid-size car / mid-size luxury car). Potential compromises in performance as well as in driving or passenger comfort are most critical in this class. Nevertheless, FEV's Hybrid-BEV approach can be applied accordingly to different segments including also LCV or other commercial vehicle segments.

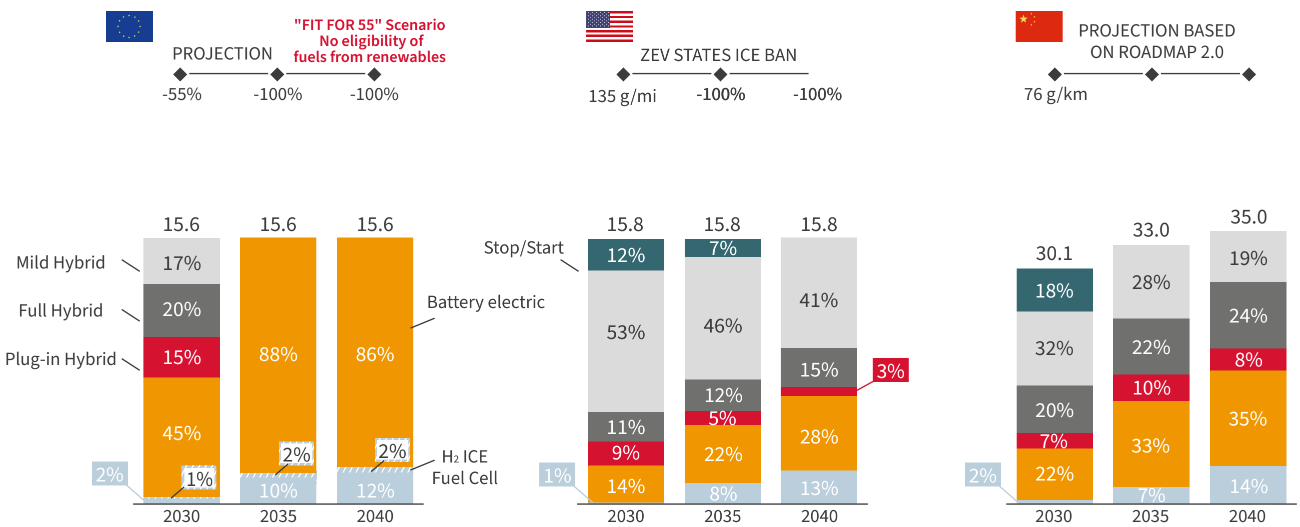
Specifications of a single platform concept

How should a hybrid vehicle (based on a BEV native platform) perform to cover a large part of drivers' current mobility needs? Data obtained by FEV in Germany from end-customer surveys provides information: Only three percent of all trips are longer than 100 km, but this three percent account for 27 percent of the total car mileage. On the other hand, only eight percent of the car milage results after 100 km. With an electric range of about 130 km, customer requirements as well as future global certification or taxation criteria are met. Nevertheless, a total range of 1,000 km was defined, meeting the "unlimited" condition and is also a value known to many company car users with a conventional Diesel powertrain. This means, a BEV native (serial) hybrid car must cover the remaining 870 km in charge sustaining mode.

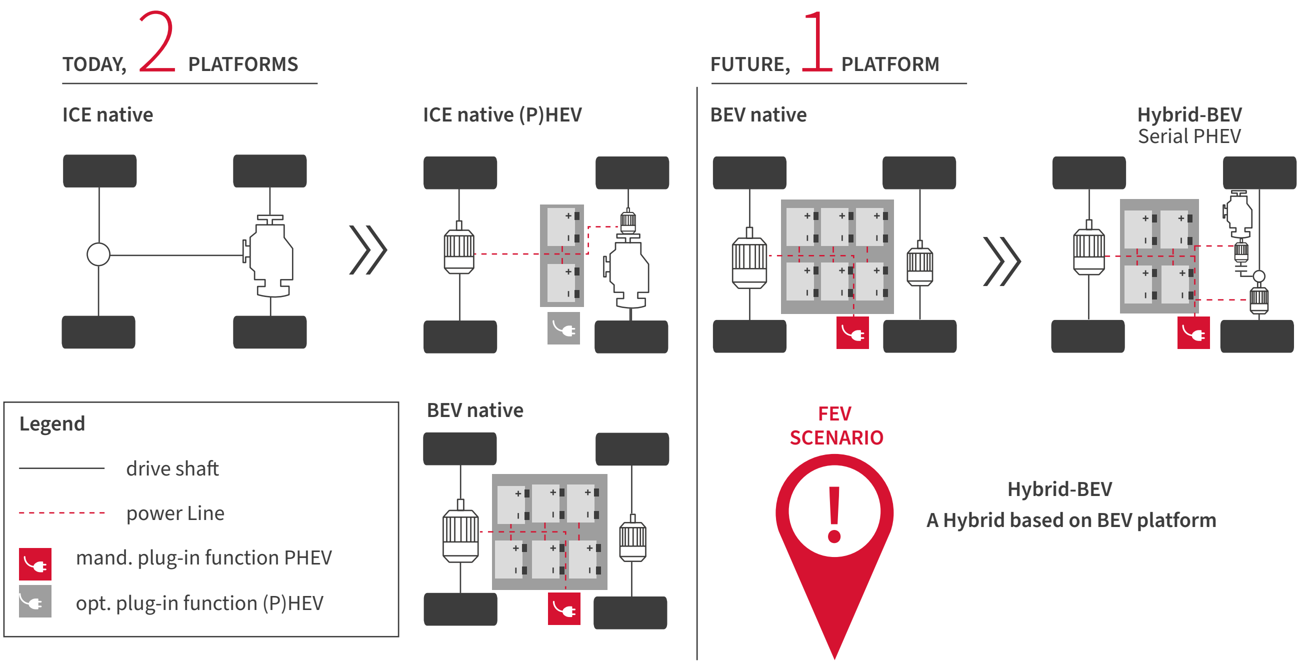
Drawing concrete technical data for the powertrain from these requirements, the following performance targets result for an SUV in the D/E segment: an e-drive power of 215 kW (315 kW for 4WD) with a battery capacity of 27 kWh. Fuel tank is assumed to be less than 40 liters considering a highly efficient powertrain. The ICE with a power of about 90 kW allows no performance degradation with empty battery. The ICE-native serial parallel Hybrid is equipped with 2.0 l 4 Cylinder and 135 kW.

An electrified powertrain also offers the opportunity to optimize the front-end package to shorten the front overhang of a vehicle. Styling is a dominant part of the customer decision, and a minimized front overhang remains in many cases a styling requirement. Furthermore, it allows the increase of the wheelbase without a parallel increase of the overall vehicle length. And it enables a comfort improvement for the customer by an increased couple distance and interior space. Nevertheless, the ICE with a power of about 90 kW is packaged in the front (transverse) for NVH and weight balancing reasons. It also makes easier access to the heat-exchanger in the front. The generator and the inte-

EU-accelerated transformation scenario, US announcements not yet considered – October 2021



① *Potential Vehicle Sales Scenarios: Global shift to more zero-emission vehicles, Europe in lead, nevertheless globally the ICE remains important even in 2040*



② *FEV's Hybrid-BEV is an all-in-one solution that eliminates the need for additional platforms*

grated front EDU for the 4WD versions could be packaged using a compact permanent magnet motor.

The analysis of the seating height shows a typically challenging aspect of the development of BEV platforms. The integration of the high voltage battery leads to a decrease of the seating height in the first and second row. That must be compensated by an increase of the overall vehicle height to keep the headroom and comfortable ergonomic values. For the hybrid variants, the space of the original BEV battery is used for a smaller, dedicated PHEV battery with 27 kWh giving room to a foot garage for the rear row of seats, also for the fuel tank and the exhaust system.

CO_2-emissions of a BEV native hybrid

One of the dominant questions of FEV's approach is, if the serial Hybrid powertrain comes with a significant drawback in CO_2 emissions compared to an optimized serial or parallel hybrid based on a native ICE platform.

The result: According to the WLTP cycle, a hybrid version (based on FEV's Hybrid-BEV concept) emits 1 g CO_2/km more than a state-of-the-art serial Hybrid. Measured according to the well-to-wheel based Japanese emissions standard, it was 3 g CO_2/km more. So FEV's PHEV concept for an SUV in the D/E-segment had no significant drawback in CO_2 emissions, they are not a critical

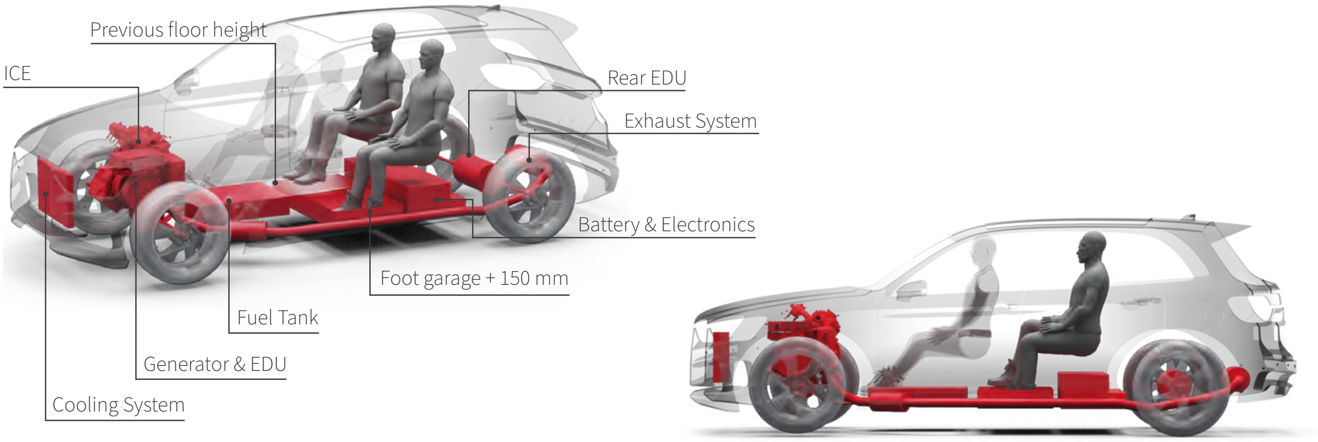
Performance Targets

Acceleration 0-100 km/h	≤ 8 s (2WD) / ≤ 6.5 s (4WD)
V_{max} @ 0% road grade	≥ 185 km/h (emtpy battery)
V_{max} @ 7% road grade	≥ 90 km/h (1600 kg trailer)-
V_{max} @ 12% road grade	≥ 60 km/h (1600 kg trailer)-
V_{max} @ 30% road grade	≥20 km/h and 100 m (600 kg payload)-
Pure electric driving range (WLTP)	~ 130 km
Total range	1000 km

Powertrain Specification

	Hybrid-BEV (serial Hybrid)	Hybrid-BEV 4WD Version	Serial Hybrid
ICE	1.5 L 3 Cyl. 90 kW		2.0 L 4 Cyl. 135 kW
EM	150 / 215 kW	+ 70 / 100 kW	45 / 65 kW
GEN	109 / 156 kW		56 / 80 kW
Transmission	1 gear EDU		4 Gears DHT
Battery		27 kWh	
Tank volume		~ 40 L	
Voltage level	800 V (same as BEV)		400 V

③ *Performance targets and powertrain specifications*



④ *Illustration of the Hybrid-BEV platform package*

parameter for the decision of the hybrid concept in a D/E-segment PHEV (Figure 5).

Further innovations will enhance these favorable consumption and emission figures in the future. For example, the power density of electric drives continues to improve. The generation of e-drives expected for the year 2030 will come with pure oil cooling (no water jacket necessary to cool the inverter), coaxial 1-speed designs, full waste heat recovery combined with heat pump, 800 V and Silicon Carbide (Si-C) inverter technology.

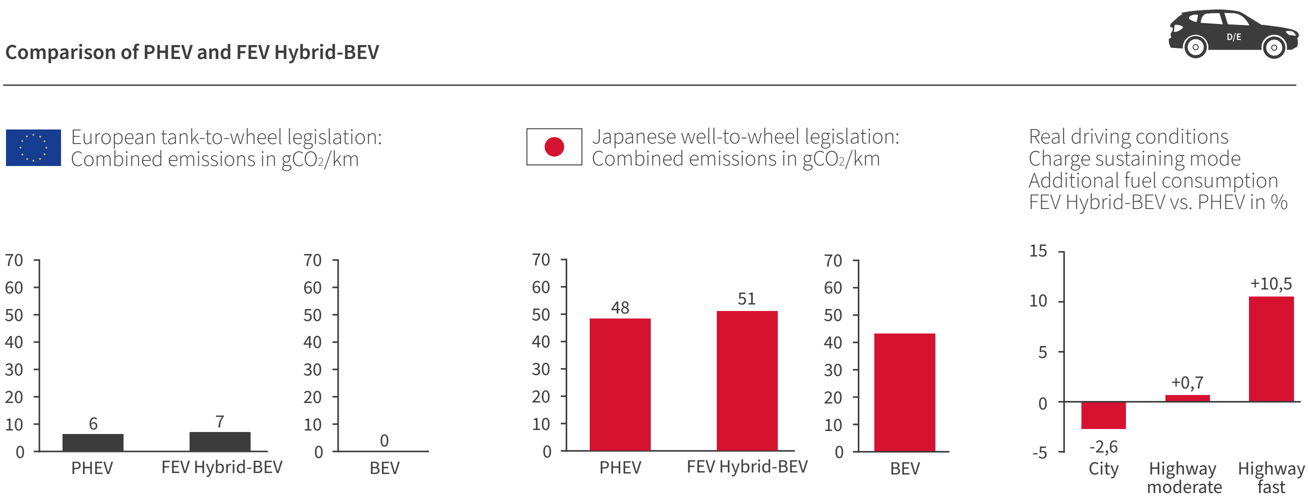
The serial hybrid also allows additional degrees of freedom in the design of internal combustion engines, making effective peak efficiencies of over 45 percent achievable at lambda = 1. The sum of these measures enables the future serial hybrid powertrain to achieve comparable fuel consumption to a parallel hybrid with mechanical through-drive even at highway speeds within the (guideline) speeds permitted in Europe. Only at very high speeds, such as those only permitted on German autobahns, would the double energy conversion have a negative impact on fuel consumption. In city traffic, the hybrid BEV achieves better consumption figures.

But how does charging behavior impact the real emissions of an xHEV vehicle based on a BEV-native platform? FEV conducted further studies based on a FEV “adjusted business driver cycle”. It assumes a 23 km trip to work, smaller leisure trips on the weekend and a monthly business trip of 300 km as well as a monthly family trip of 200 km (all numbers are one-way distances).

Charging the battery once (twice / three times) a week already leads to low CO_2 emissions of 86 (72 / 58) g/km, while charging the battery before each trip causes a further reduction to 30 g CO_2/km. So, for a typical FEV business car driver (who drives four times more long distances than the average one), charging the battery twice a week leads to CO_2 emissions of 72 g/km equaling 3.1 l/km for a D/E segment SUV.

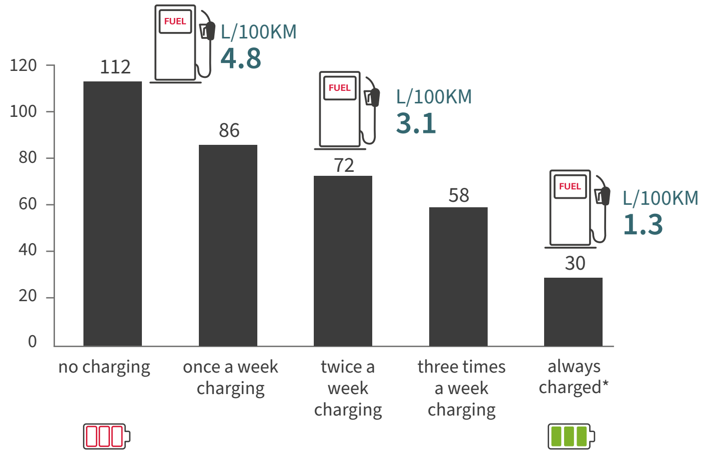
The FEV study also shows, that the transition to the single-platform approach is not only feasible from a technical point of view, but also economically attractive. It helps smaller OEMs and start-ups in particular to realize significant cost advantages. They can also meet current customer expectations and needs for a vehicle with different drives in the D/E segment on one BEV platform without much additional effort.

Comparison of PHEV and FEV Hybrid-BEV

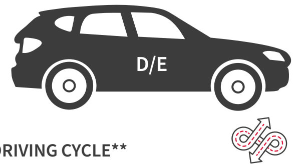


⑤ *Comparison of PHEV and FEV Hybrid-BEV for Japan and EU as well as under real driving conditions in charge sustaining mode*

CO_2 emissions of Hybrid-BEV with 1.5 l 3-cylinder DHE with 45% efficiency in gCO_2/km



* Every trip has started with fully charged battery
**Adjusted to expected reduction of business trips due to higher share of online meetings



ADJ. FEV BUSINESS CAR DRIVING CYCLE**

- **Daily travel to work**
  – Distance to FEV: 23 km (one way)
- **Small leisure trips on the weekend**
  – Distance: 12.5 km (one way)
- **One business trip to customer per month**
  – Distance 300km (highway – one way)
- **One weekend family trip per month**
  – Distance 200km (highway – one way)

CAR MILEAGE ABOVE 100KM Distance

German Average 8%

FEV Business Driver** **33%**

⑥ *Impact of battery charging behavior on real-world CO_2/fuel consumption for FEV's BEV Hybrid approach*

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3 Questions to ...

Dr. Tolga Uhlmann, Vice President Motor & Hybrid Powertrains, FEV Europe GmbH

A serial hybrid has been around for some time. What's new about FEV's Hybrid-BEV platform?

With few exceptions, the known serial Hybrid vehicles are based on ICE native platforms. So, the current shift towards e-mobility implies a two-platform strategy for OEMs: ICE native and BEV. We have now investigated how hybrid variants can be derived based on a BEV platform only. Such a single-platform strategy is significantly more cost-efficient and brings advantages particularly for smaller manufacturers or start-ups.

What are the benefits from the end customer's point of view?

The "classic" range-extender typically inhibits reduced driving performance in case the battery is depleted, whereas the ICE-based PHEV with a mechanical connection has the feel and the look of a conventional ICE powertrain in charge sustaining mode. This is not the case for our Hybrid-BEV: It offers full driving performance under all conditions and in combination it has the feeling and look of the driving experience of a real BEV and achieves very good CO_2 emissions due to the highly efficient energy conversion system.

Are hybrid variants still attractive? In view of ever stricter emission legislation, the trend is clearly toward purely electric drives.

On the one hand: Yes, and that's why instant effects are particularly important. When it comes to reducing emissions, a PHEV remains an attractive solution. We have calculated that even the strict requirements of the EU Commission, their "Fit for 55" program, can be achieved through a fleet mix of BEVs and xHEVs. At 27 percent, the BEV share would even be comparatively low.

On the other hand: Every OEM needs to develop BEV-platforms, but most OEM cannot dispense the business car driver who aren`t yet ready to do the step towards pure electrification. After all, our proposed single-platform approach based on a BEV aims to make the transition to pure electromobility as cost-efficient as possible - not only for smaller OEMs or start-ups. Since vehicle demand in general is still highly volatile at the moment, this gives them the flexibility they need for their model planning.

FUEL CELL FREEZE START

BREAKING THE ICE: MAKING FUEL CELLS WINTERPROOF

For fuel cell EVs to become a real alternative to combustion engine vehicles, their operation under severe sub-zero conditions needs to be improved – a challenge that FEV has accepted.

Fuel cells for vehicle propulsion have a long track record. Without any doubt, this technology has the potential to contribute significantly towards zero emission and zero CO_2 mobility provided the hydrogen stems from renewable energies.

However, further research and development is fundamental to make fuel cell electric vehicles (FCEV) an efficient and competitive alternative to combustion engines and battery electric vehicles (BEV) for both heavy duty and passenger cars. Economies of scale will then apply just as much to FCEVs as they do to BEVs. Especially for heavy duty and long-haul applications the high energy density of hydrogen and fast refueling times matching those of petrol make fuel cells an ideal solution. Furthermore, high durability and reliability are mandatory. Research conducted by FEV has already shown that the lifetime of fuel cells can be further improved.

Corrosion of bipolar plates, catalyst degradation and membrane degradation are the three main factors impairing the lifetime of fuel cells. Research for instance investigates what materials should ideally be used for the bipolar plates which constitute a core element of fuel stacks. Using graphite-polymer compounds rather than pure graphite plates might be an intelligent solution.

① *FEV test vehicle Hyundai Nexo*

Freeze-start as a major challenge

Besides cost reduction and aging effects, freeze starts of the system under severe sub-zero temperature conditions, remain a challenge. Faced with a multitude of choices when designing the rather intricate fuel cell system (FCS), it is a matter of identifying the best possible compromise. The compromises may finally vary from one FCEV to another, depending on the vehicle's overall architecture and what expectations are attached to its performance, reliability and lifecycle.

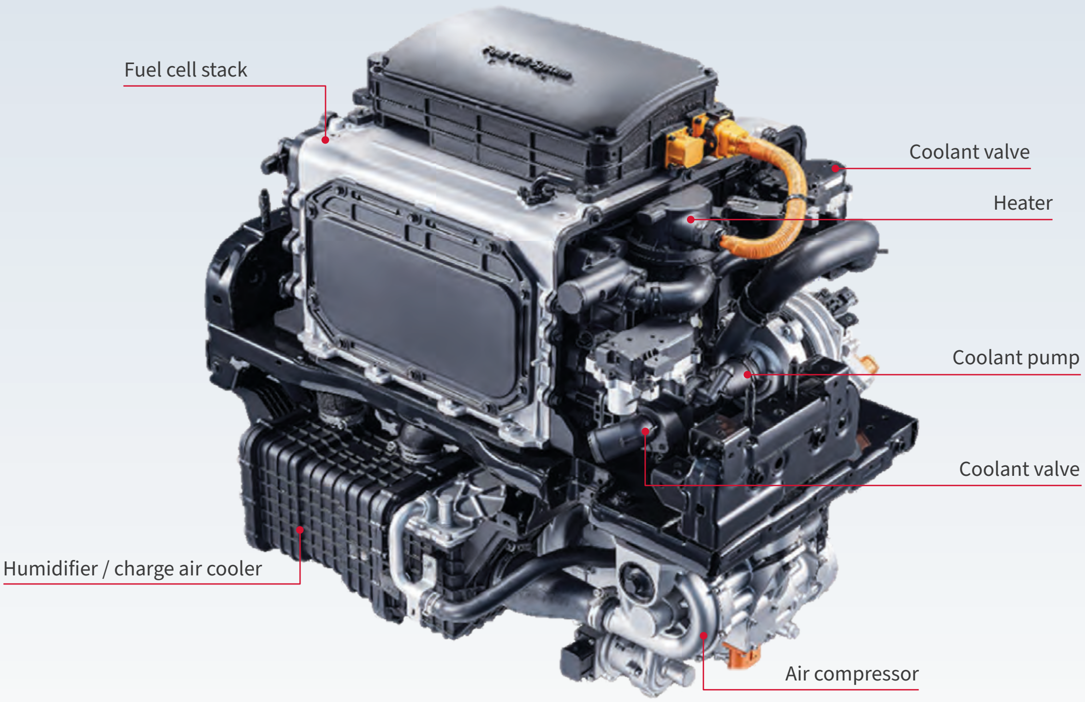
Based on the Hyundai Nexo, FEV has closely examined the aspect of freeze starts, which in many respects puts the fuel cell system under a lot of strain exposing it to wear and tear. Thus, FEV experts have investigated under what circumstances and at which point the cell product water is likely to freeze, thereby not only preventing a successful startup process but also permanently damaging the cells.

Regarding freeze start, to better understand its effects at the cell level, detailed multi-dimensional computational fluid dynamics (CFD) studies were conducted. Starting from a temperature of -30 C, the startup process was simulated using cell sections while considering the different freeze start processes in time. Furthermore, the possibility of 1D system simulations was elaborated.

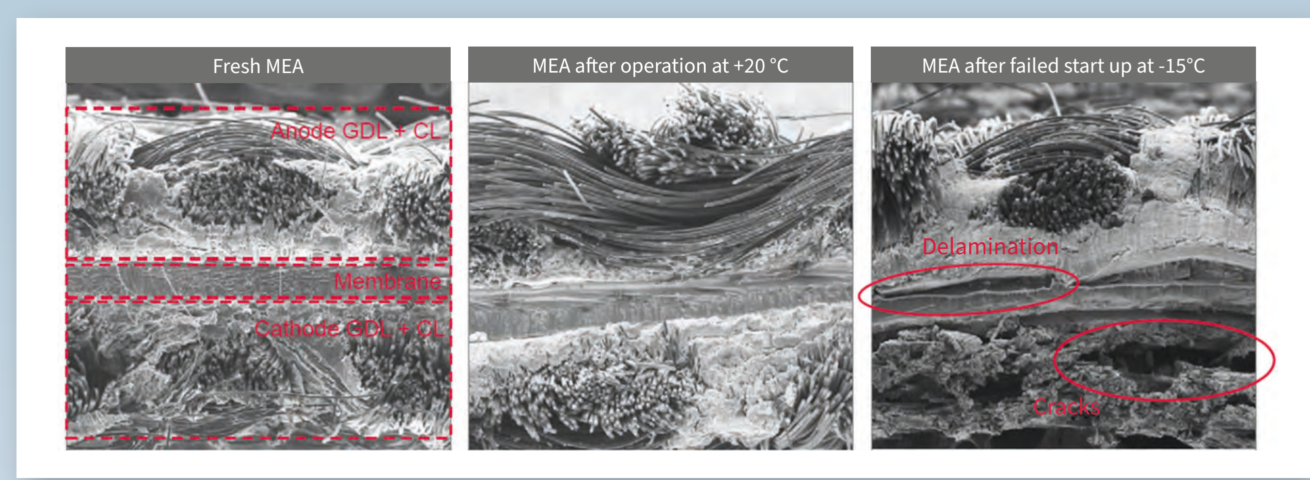
Ice in the system is the enemy

As a matter of fact, the above-mentioned degradation mechanisms, i.e. corrosion, catalyst and membrane degradation, are greatly amplified by fuel cell freeze starts. To avoid damages to the membrane electrode assembly, MEA, or gas diffusion layer, GDL, resulting from ice formation within the cell, many freeze start strategies are applied within series production fuel cell vehicles.

During a freeze start the product water from the electrochemical reaction of hydrogen with air can form ice, if the fuel cell stack is at sub-zero temperatures. Ice builds up within the catalyst layers, porous layers and within the flow channels of the fuel cell. While the ice within the channel is blocking the supply of the fuel cell leading to a collapse of the cell voltage, the ice within the porous layers can lead to severe damages of the fuel cell and must be prevented at all costs. During the onset of ice formation within



② *Overview of Hyundai Nexo fuel cell system*
Picture: Hyundai



③ *MEA damages of failed fuel cell freeze start* *Picture: 10.1016/j.jpowsour.2006.02.075*

the porous media small ice lenses block the pores reducing the gas transport, leading to reduced cell performance.

With increasing amounts of ice, the electrochemically active areas progressively decrease, resulting in further performance losses. Finally, the ice fills all voids within the porous media, and due to the expansion of the ice high mechanical stresses are induced in the cell layers. These stresses result in delamination of the membrane electrode assembly layers and formation of cracks in the catalyst layers as well as gas diffusion layers.

How to get a well-tempered system

It is not a question of whether FCEVs can perform a freeze start, the challenge is to improve the startup procedure under extreme sub-zero temperatures, both regarding the longevity of the FCS and the time elapsing from ignition till the moment when the driver can use the system's full power. For moderate sub-zero temperatures this is not an issue. However, when it comes to temperatures as low as -30° C, the fuel cell startup is mostly performed successively. Here, the driver has to allow for up to 60 seconds for the startup procedure itself and approximately another 60 seconds before the Nexo can deliver full power.

Many measures are available to facilitate the freeze start of fuel cells. These include the design optimization of the stack, cell and MEA as well as operating strategies and external methods to assist the freeze start. For a successful and fast freeze start a combination of all these strategies is usually applied, not to forget an efficient shutdown procedure.

One possible shutdown strategy is to keep the fuel cell warm during the time the vehicle is parked. This can be realized either by insulation or by constant operation in order to generate sufficient heat and thus prevent the stack from freezing. In practice, however, these measures usually are not applied since the parking duration is unknown and fuel is being wasted. Therefore, common practice is to purge the stack before shut-off to drain as much water from the fuel cell as possible. This is achieved by turning off the hydrogen supply and increasing the airflow through the stack.

If the fuel cell system is fitted with a humidifier, the latter is ideally bypassed to decrease drying times. This prevents ice formation before the fuel cell is even started and increases the water capacity of the membrane during the freeze start. After the stack is dry, inerting of the cathode is started by closing the shut-off valves and the humidifier is dried to prevent ice formation in this component.

Freeze start strategies must aim to produce as much waste heat as possible to quickly heat up the stack while protecting it from damages resulting from excessive ice formation or degradation effects. In general, the stack during startup can be controlled either by the current or the voltage.

Stack and cell design

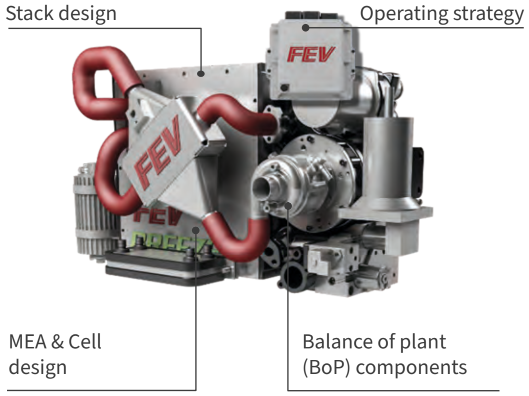
When designing a fuel cell stack its thermal mass can be reduced through a careful selection of the used materials, the material thickness, as well as an optimized usage of material in general. A lower thermal mass requires less energy for heating up facilitating freeze start. Besides the stack design a flow-field design of the bipolar plate with high water removal capability is key for a fast and successful freeze start.

To name just a few other parameters that impact the FCS: Thinner MEAs exhibit faster water uptake. Hence, the product water during freeze start is absorbed by the membrane and cannot undergo phase transition to form ice. For this reason, membranes with higher water capacity also aid the freeze start. However, thinner membranes can have a negative effect on fuel cell lifetime. Therefore, a trade-off between both targets must be found.

Catalyst layers (CL), for their part, with thicker layers and higher ionomer content help to bring down the freeze start times. But this comes at a cost, viz. higher precious metal loading plus possibly lower durability.

The design of the micro-porous layers (MPL) and GDL are also having an impact on the freeze start capabilities of a fuel cell. On the one hand, the addition of a MPL facilitates water removal from the surface of the catalyst layers and increases the ice capacity of the CL. On the other hand, blocking of the MPL pores might lead to ice accumulation on the interface between CL and MPL resulting in high local pressures and damages of the catalyst layer such as pinholes and micro cracks.

Many conflicting issues need to be weighed carefully. Not to forget the advantages and disadvantages of high versus low current or the length of the gas channel and its effects on the formation of ice under extremely low temperatures, to add but a few more factors.



VEHICLE REQUIREMENTS

Fuel cell start up at temperatures as low as -30°C

Driver wants to start journey as fast as possible:

- Freeze start times at moderate sub-zero temperatures: immediately
- Freeze start times at very low temperatures: ≤ 60 s

Driver needs full power when entering the highway or leaving city bounds:

- Full power delivery ≤ 2 min after ignition

④ Factors of fuel cell systems for freeze start capability

Assisted startups successfully managed

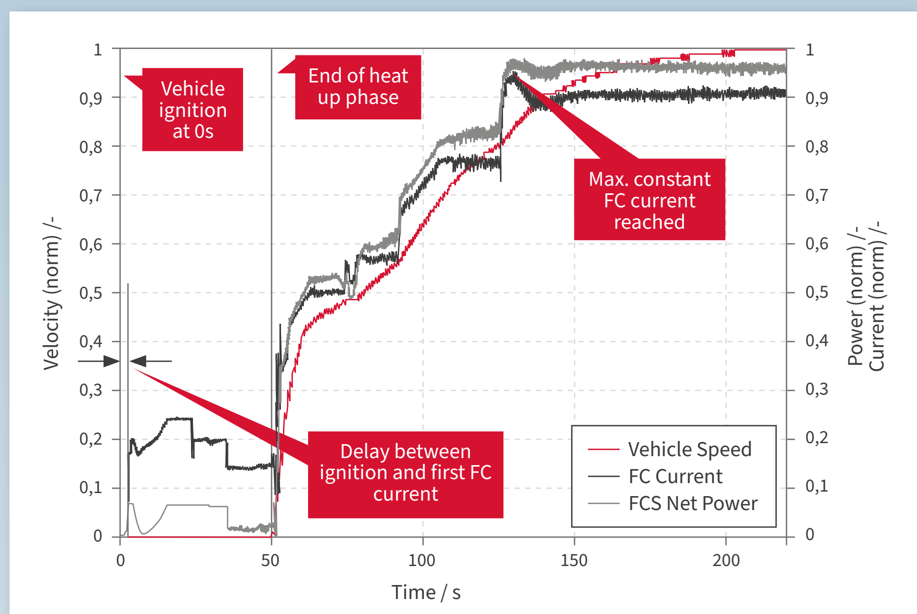
Through current ramping a combination of the advantages of a high and low current mode can be achieved. During the ramp-up phase of the current example of the Nexo fuel cell system, current ramping is used to gently heat up the stack while avoiding excessive ice formation. As soon as the voltage of the individual cells begin to stabilize, a high current plateau is maintained resulting in high heat generation by the fuel cell.

After the initial high plateau, the cells are sufficiently stabilized and the air flow rate is reduced to avoid drying of the membrane, and since the membrane water capacity has increased, the product water is absorbed and ice formation is slowed down. The reduction in compressor power leads to a drop in fuel cell current and this current level is maintained until the cells have further stabilized.

When the last plateau of the initial phase is entered all cells are stable, showing low cell-to-cell variation. This is when the end cell heaters are deactivated. The initial phase is completed once the electrical heater outlet temperature is above sub-zero temperatures. From turning on the ignition until full power operation approximately 120 seconds have elapsed.

Computational fluid dynamics delivering reliable results

Faced with a daunting multitude of variables that intricately interact at various levels within the setup of the FCS, FEV resorts to computational fluid dynamics (CFD) in order to gain as precise an insight as possible into what to all intents and purposes could be the best design for an FCS.



⑤ *Freeze start procedure of a fuel cell vehicle*

Knowledge of the exact geometry is paramount for a CFD simulation. The geometry of the fuel cell must then be discretized so that the model equations, which cannot be solved analytically, can be solved iteratively with the help of the grid points created in this way. However, the available computational power is limited because the necessary number of computational cells, i.e. the number of discrete grid points, increases with increasing size and complexity of the geometry under consideration. For this reason, depending on the goal of the investigations, it is not practical to simulate an entire stack or an entire cell. For most cases it is sufficient to investigate a single gas channel or a small section of a cell.

A very strong abstraction of the stack geometry allows the complexity of the model equations to be high. At the same time the simplified geometry of the fuel cell keeps the number of computational cells and thus the calculation time within reasonable limits.

After thus establishing a fundamental understanding of the process of ice formation within the different layers of the cell, a reduced model within the framework of a 1D simulation can be set up. This is done to optimize the freeze start operating strategy as well as assess different components assisting the freeze start.

The benefits of FEV's detailed freeze start modeling on the cell level are obvious: This analytical approach generates masses of data which are used to calibrate a three-dimensional CFD model of the cell to provide further insight into the phenomena occurring on cell level during the freeze start.

Such analyses are immensely important to help further improve the reliability, longevity and efficiency of fuel cell systems. The FEV engineers are convinced that based on their analyses there is still a lot of room for making the fuel cell system yet more robust and efficient at cold temperatures.

Summary

Automotive applications must provide swift freeze start-ups without causing any damage. Based on its huge database, FEV with its profound knowledge of shut-down and freeze-start procedures is investigating how freeze starts can best be achieved without impairing the functionality or lifetime of the stack. For doing so FEV draws valid conclusions both from 3D-CFD investigations and 1D fuel cell system models avoiding a conflict of objectives.

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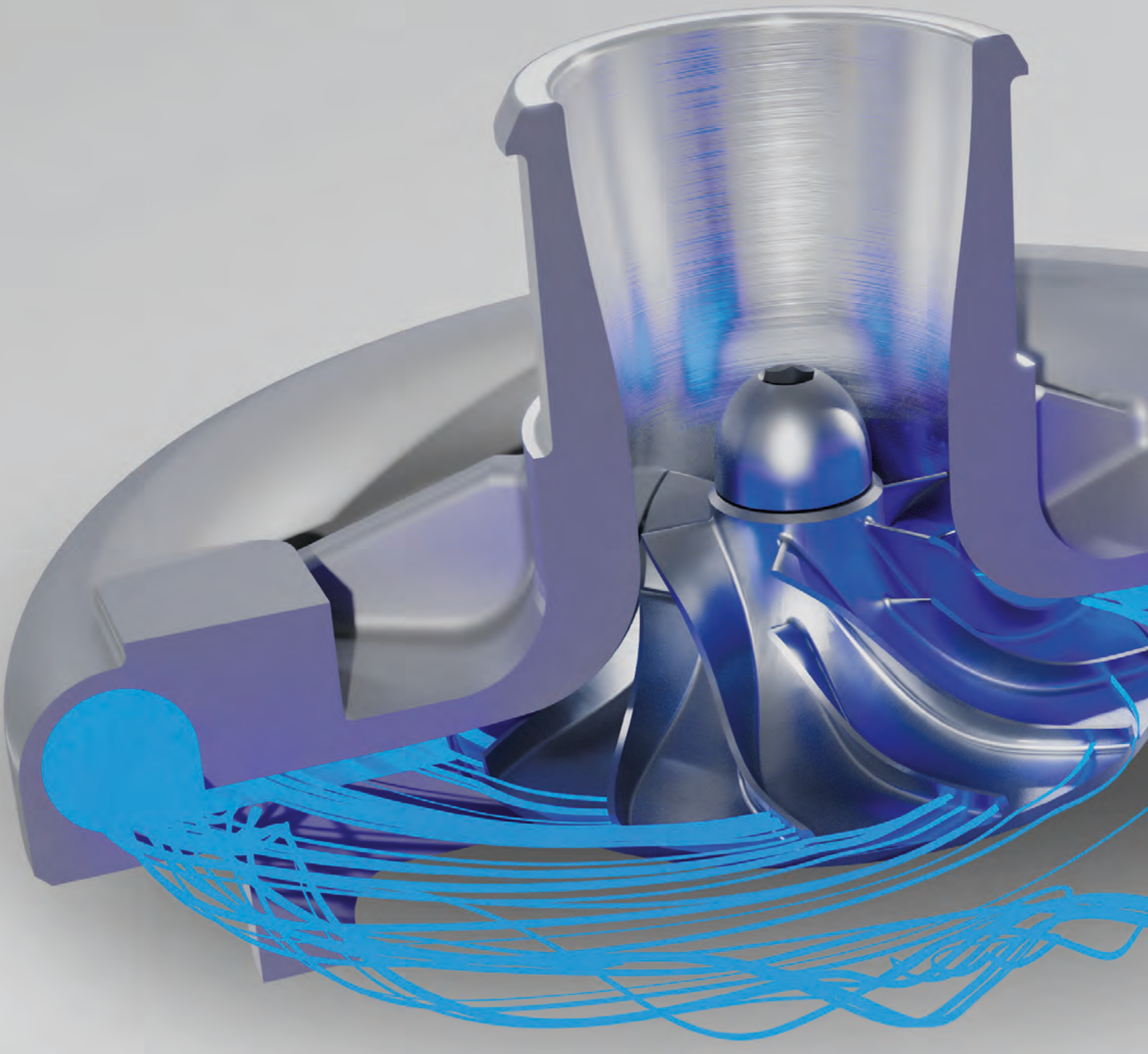
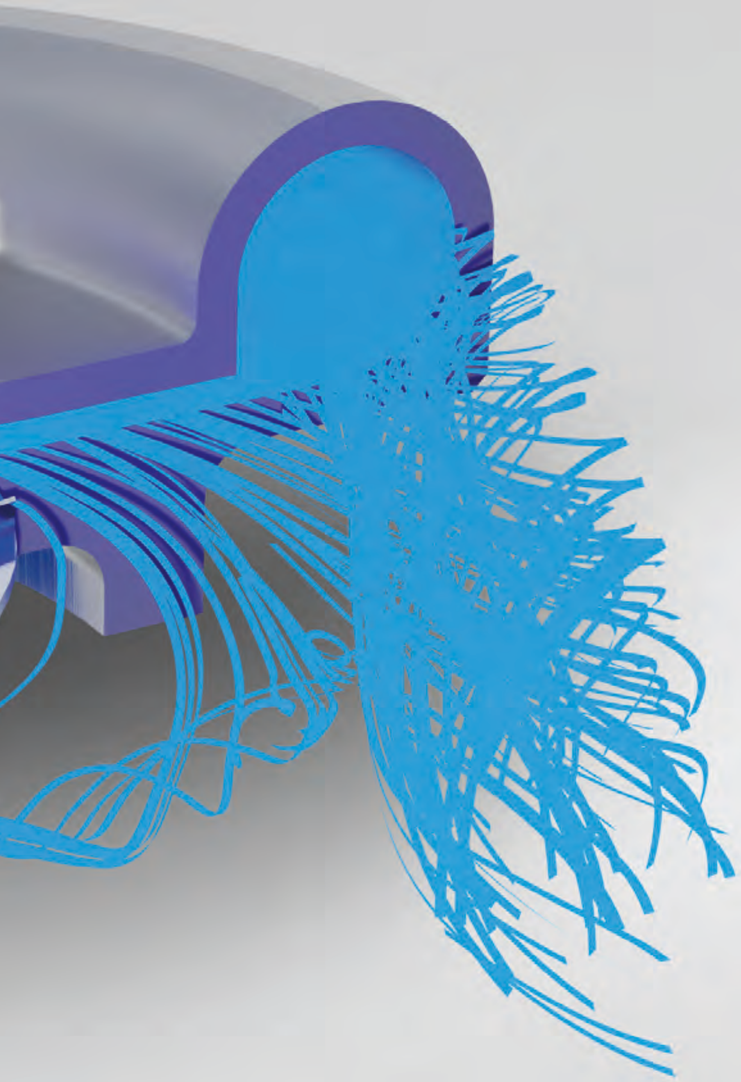
FUEL CELL COMPRESSOR DESIGN

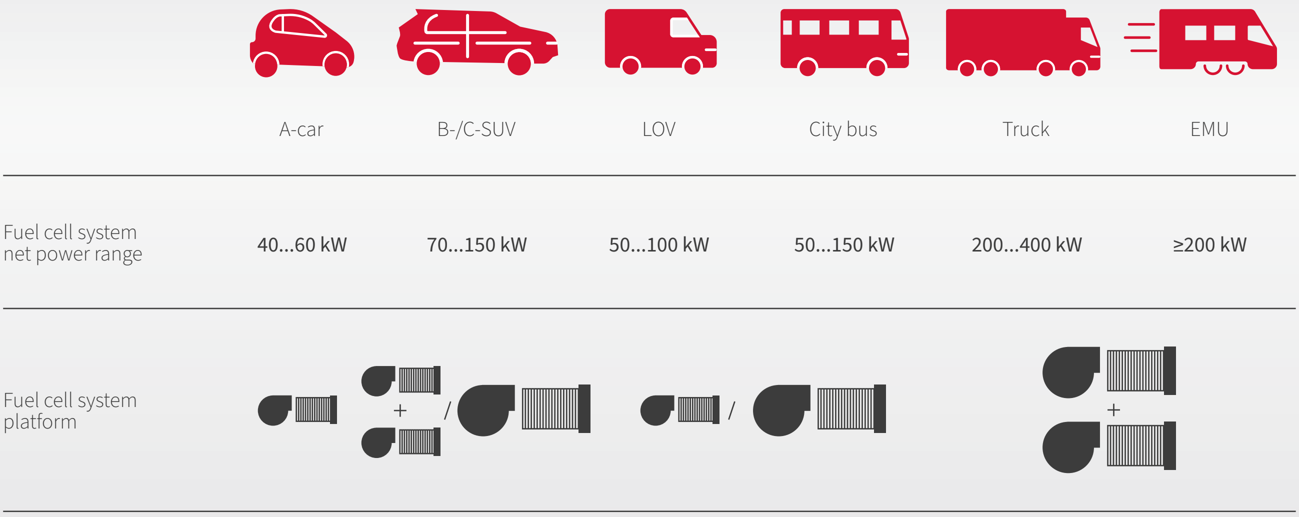
SIMULATION CUTS COSTS AND OPTIMIZES EFFICIENCY

Supercharging makes a lot of sense regarding power output of fuel cells. However, the wide range of applications and limited volumes in the near term make development of tailored compressor designs expensive. The solution is a holistic simulation process, which FEV has now demonstrated for the first time.





Global passenger car markets are expected to shift towards electrified powertrains in the next years. Electrolyte membrane fuel cells (PEM-FC) are being discussed in particular for commercial vehicles such as heavy-duty applications or public transport. However, currently PEM fuel cell powertrains are employed predominantly in passenger car applications. Further potential for the use of fuel cells as a central energy conversion unit exists in the field of off-highway and train applications as well as in aviation. So far, the PEM fuel cell is still a niche product and has not been able to establish itself in the mass market.



① *Fuel cell system and compressor scaling approach for various applications*

One reason for this is the wide range of requirements of the applications mentioned before regarding performance, service-life, size and weight. This might change in the near future: Starting from 2030, the introduction of over 60 million fuel cell vehicles is forecast. Japan and South Korea are expected to be the first movers towards fuel cell vehicles showing already significant market shares by 2030. Regarding on-road commercial vehicles, the heavy-duty vehicle segment will be a key driver, for example in Europe, due to the implemented stringent CO_2 emission regulations, but also in Japan and South Korea.

The required fuel cell system power output is ranging from approx. 40 kW in the A-car segment to 400 kW in heavy-duty applications. In order to cover the wide range of power, modularization and platform strategies are required for fuel cell systems and their components.

Depending on the point in time during the market ramp-up and depending on the volume per application, different modularization strategies are appropriate to balance development and manufacturing costs ranging from a strong modularization approach to a strong tailoring.

Compressor as an essential fuel cell component

During market introduction phase, the use of multiple components in a single system such as air compressors is a probable solution. With increasing production volume of fuel cell systems, electric motor / inverter platforms of the compressor expander unit (CEM) are expected for the different fuel cell system power levels. For performance optimization, the compressor and expander wheels need to be tailored to the fuel cell system requirements.

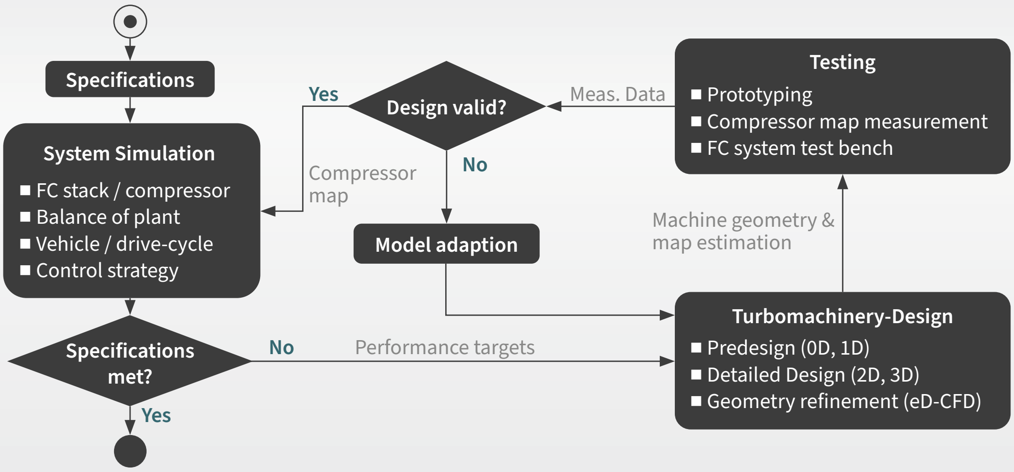
Supercharging of the cathode air facilitates increasing system efficiency and power density. Electrically driven radial compressors are typically used for this purpose, as they outperform other compressor types in terms of efficiency, cost and acoustical behavior. Due to the currently low production quantities of fuel cell systems, only a limited budget is available for air compressor development. Consequently, application tailored compressor design is oftentimes not economically feasible and therefore omitted.

This is, where simulation-based compressor design comes into play. It allows the development of tailor-made compressors for the respective fuel cell system or application. The holistic nature of the design process also promotes an understanding of the interaction between the different subsystems and thus enables the compressor- as well as the system- or powertrain-manufacturer to specify profound design targets. Development costs and time can be saved while at the same time increasing overall system efficiency.

Steps of the compressor design process

In the first step, a holistic design process as suggested by FEV must take into account the relevant boundary conditions. In addition to high efficiency and broad map width (cf. automotive turbochargers), additional requirements must be fulfilled by radial compressors for fuel cell applications: Maximum compressor operating speed is limited by the electric machine and by the air foil thrust bearing disk (maximum root stress). In addition, a certain electric drive power reserve must be provided for transient operation.

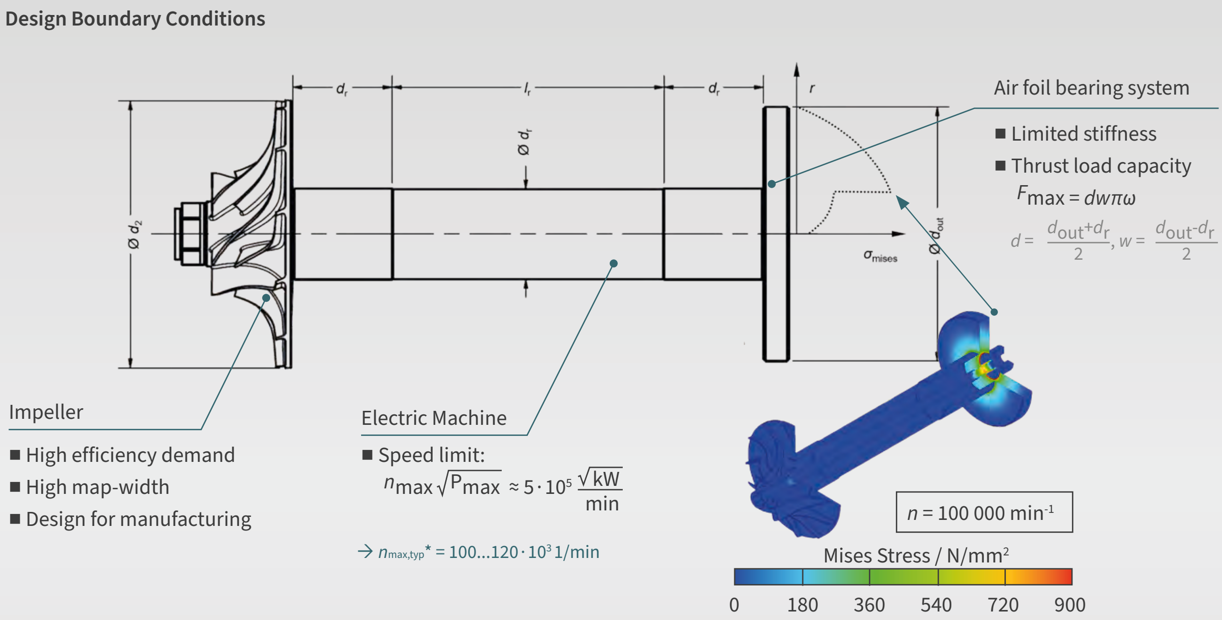
In the second step, an 1D system simulation model can be used



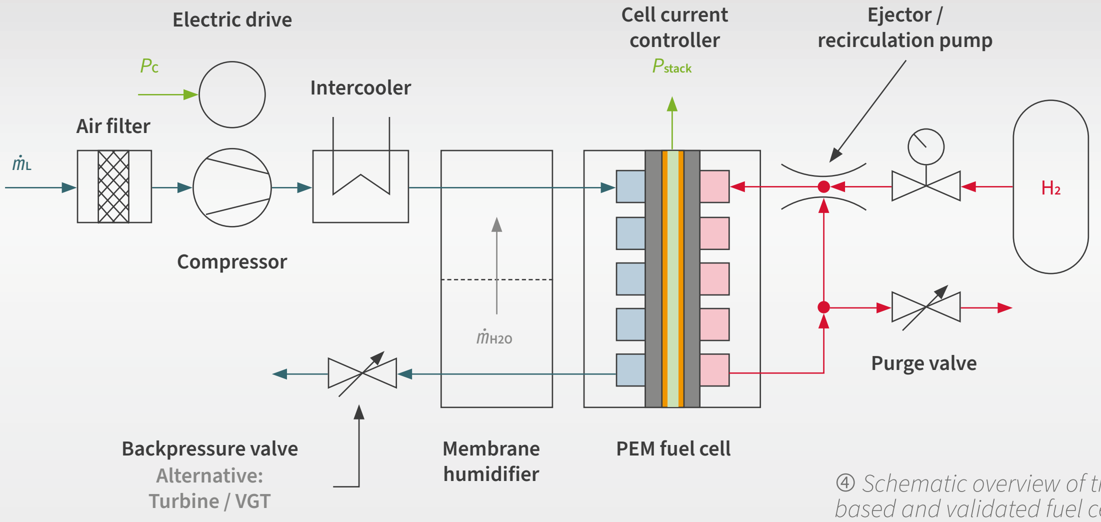
② *Process flow chart of the fuel cell air compressor design process*

to derive the basis for the detailed compressor design for which the potential of expansion turbines is examined as well.

The boundary conditions consist, among other things, of the vehicle specification (e.g. vehicle class, weight, drive cycle, and more) and the desired properties of the fuel cell powertrain (target power, efficiency, size and weight, hybridization). With the help of fuel cell system, powertrain and vehicle simulations, these boundary conditions are translated into performance target values for the air compressor.



③ *Example of boundary conditions during the holistic design process*



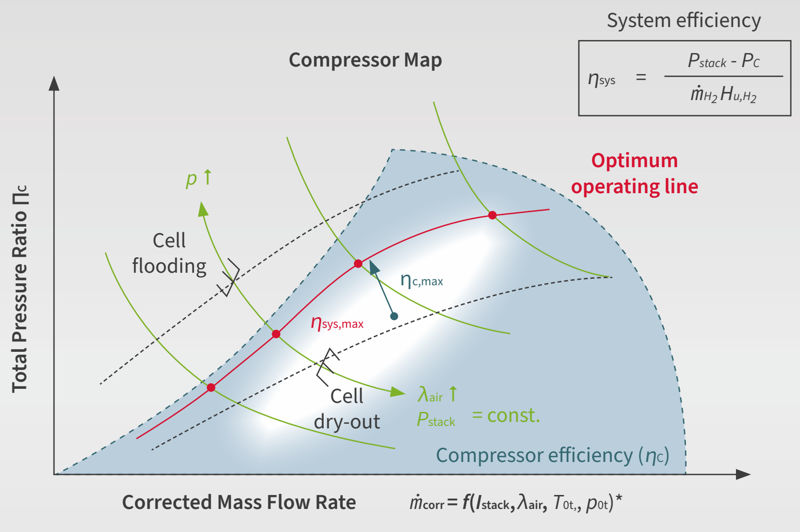
④ *Schematic overview of the physical based and validated fuel cell system model*

After successfully deriving these performance targets, the compressor stage can be designed accordingly. During the predesign phase, a large number of design candidates (more than 1.000) is investigated using 1D streamline simulations with low computational effort. The target geometry and machine meta-parameters will be automatically generated and evaluated by means of computerized optimization algorithms.

During detailed design, the most promising design candidates (less than 100) are used for the refinement of the flow path geometry. Blade angle distribution, diffuser contour, volute shape and similar parameters are set at this point. The last design step is the geometry refinement where a limited number of design candidates (between 10 and 20) is investigated using 3D-CFD and finite element analysis. This step is necessary for the verification of the detailed design with regards to aerodynamic performance and structural integrity. Local adaptions e. g. of the leading edge shape or blade thickness profile are made to optimize performance and efficiency.

To accelerate the development process and to allow for quick design iterations, the integrated toolchain presented in the following figure was implemented.

The toolchain is governed by a compressor design tool developed by FEV. This software package is capable of geometry generation, preliminary design (1D performance analysis based on empirical loss correlations and structural analysis), throughflow calculation (quasi 3D inviscid flow simulation for inlet cone, impeller and diffuser) and reverse-engineering (tactile and optical impeller metrology). 3D models can be directly exported to commercial computer aided design CAD and engineering CAE

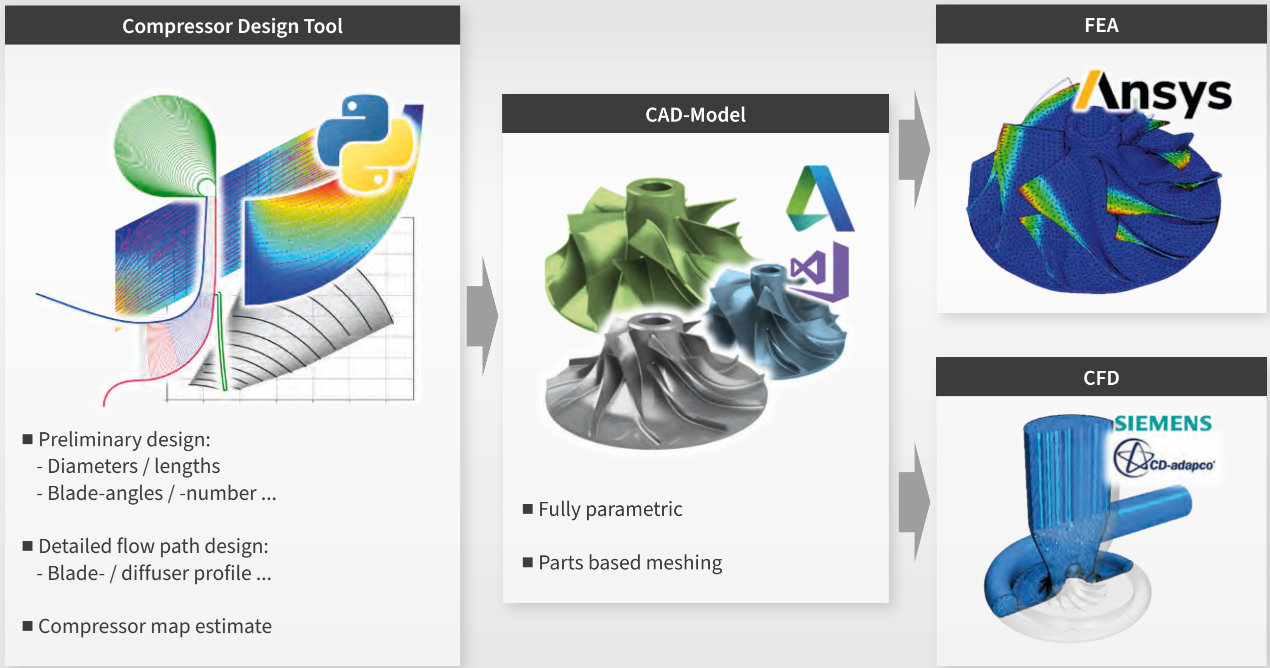


*) $\dot{m} = \lambda \cdot L_{st} \cdot \dot{m}_{H_2} = \lambda \cdot L_{st} \cdot n_{Cells} \cdot \frac{I_{stack}}{2F} \cdot M_{H_2}$ **) Feasible operating points above λ_{air}, p curve omitted for simplicity

Approach

- Stack power/ efficiency increase by
  - Air ratio λ_{air} ↑
  - Operating pressure p ↑
  - → $\lambda_{air}\,p$ substitution curve for constant stack-power
- Determination of optimum $\lambda_{air}\,p$ combination
  - Stack efficiency ↑↓
  - Compressor power/ efficiency ↑↓
  - Humidification level ↑↓
  - System efficiency η_{sys} → max
- Optimum compressor operating line
  → Compressor matching
  → Iterative optimization

⑤ *Simulation result is an optimum operation line for the given boundary conditions*



© Integrated Toolchain for Fast Design Iterations

software packages for further design refinement or analysis (finite element analysis FEA or computational fluid dynamics CFD). Standardized data exchange formats enable automated design optimization for large candidate sample sizes. With the aid of parametric models, changes made in the design tool can be directly assessed in FEA and CFD

Finally, the design is validated experimentally. Prototype designs are tested on an electrically driven radial compressor testbench capable of measuring impeller drive torque. Herewith, aerodynamic compressor performance can be assessed. The recorded measurement data is used to verify both the turbomachinery design as well as the system simulation. If all specifications are met, the compressor design is finalized. Otherwise, certain feedback loops over the design process will be repeated until consistency is reached.

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Summary

PEM fuel cells could end their current niche position in the immediate future and become an essential technology for the electrification of several mobility applications - from small cars to trucks and trains. The compressor will play an essential role in this process, as supercharging enables a significant increase of power density and stack efficiency at full load. Stack size (active cell cross-section) and associated costs can be reduced.

In order to also keep development costs within limits, developments based on simulation are important. The development process proposed by FEV shows such a real-time development process using the example of a compressor: Within 1D system simulation, the complex interaction of the individual components can be evaluated in a profound manner. Coupling this with the integrated compressor design toolchain developed at tme (Chair of Thermodynamics of Mobile Energy Conversion Systems, RWTH Aachen University) and FEV makes the application-specific design of the air supply system economically feasible even for small production numbers. All powertrain components (including hydrogen supply, cooling system, power electronics, etc.) can be optimally matched to the requirements of the overall system already in early development phases. Communication between the involved development partners is supported, development time and costs can be reduced.

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DEFOSSILIZATION

THE COMBUSTION ENGINE CAN BECOME REALLY CLEAN WITH HYDROGEN

The pursuit of zero transport emissions has brought hydrogen (H_2) back into play, especially for commercial vehicles. It makes sense to use this carbon-free energy source not only for fuel cells but also for combustion engines. It requires specific exhaust aftertreatment systems for nitrous oxides though. FEV researched into finding the most viable solution for that need.

When it comes to zero-emission trucks and buses, hydrogen ranks among the best answers for the long haul. In vehicles it can be used in two carbon-free ways: by being – comparable to fossil diesel – burnt in a modified internal combustion engine (H_2-ICE); or in a fuel cell that transforms it into current for an electric motor. The H_2-ICE has advantages like more robustness and lifetime, two highly relevant criteria for commercial vehicle (CV) applications. Small scale series vehicles have been sold already in the early 2000s but were not competitive in terms of specific load (engine power in relation to displacement). This manco has long been solved by boosting, that means by turbo chargers or compressors.

The only pollutant that can – under certain circumstances – still reach significant levels in a H_2-ICE is nitrogen oxide (NO_x). If these emissions are reduced to near zero without increasing others, especially secondary ones like “laughing gas” (N2O) and Ammonia (NH_3), the hydrogen combustion engine becomes a robust “green” concept. This is mainly achieved by getting rid of remaining tailpipe emissions via aftertreatment systems – and by accompanying measures. FEV analyzed, which combination of these technologies fits this purpose best. The experts based their investigation on a 7.7-liter commercial CNG-engine that was converted into a hydrogen motor. Apart from injection modifications, a two-stage turbo charger replaced the single-stage type.

Managing the challenge of a H_2-ICE’s Exhaust Aftertreatment System (EATS)

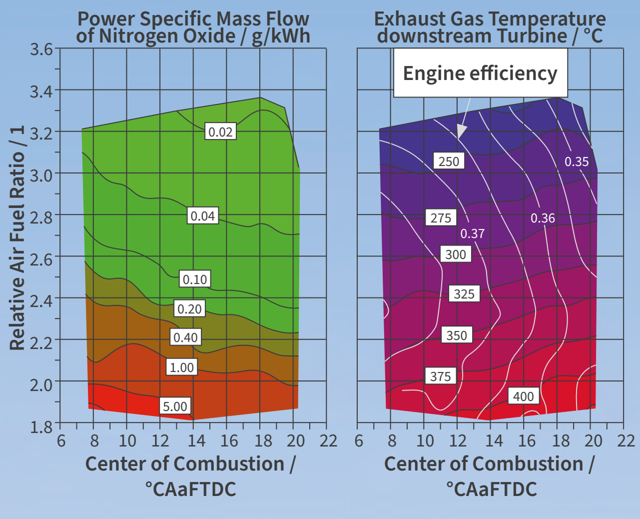
In the investigation, the NO_x target was set at a maximum 69 mg/kWh. This equals 15 percent of the current limit of 460mg/kWh according to the Euro VI legislation in the WHTC (for World Harmonized Transient Cycle, a dynamometer exhaust gas test for heavy duty vehicle certifications) All FEV tests are comparable to the official legislation procedure.

The H_2-ICE tailpipe emissions – as those of any internal combustion engine – mainly depend on the engine out emissions on the aftertreatment system efficiency. The engine out NO_x is strongly influenced by the air/fuel-ratio (λ). The most important factors for aftertreatment efficiency are exhaust gas temperature, mass flow rate and exhaust gas composition.

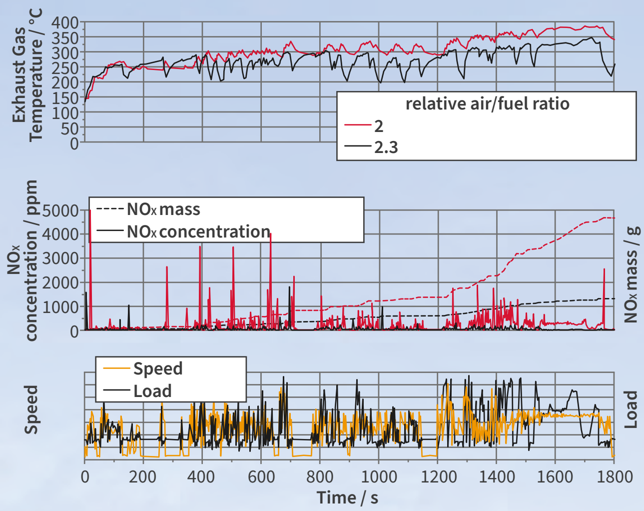
The FEV measurements show firstly the exhaust gas temperature downstream turbine, secondly the engine-out NO_x emissions, and thirdly the engine efficiency depending on the air/fuel-ratio and the center of combustion at a constant operating point (1,400 rpm, 8 bar). In fact, all three factors are significantly influenced by the air/fuel ratio.

With leaner operation (lower fuel portion), the NO_x emissions can be reduced drastically while the exhaust temperature decreases. The engine efficiency shows an optimum at approximately $\lambda = 2.3$. But trying to reduce NO_x emissions to almost zero just with internal measures would lead to a higher fuel consumption and a worse transient response. A calibration that focuses on optimized fuel consumption on the other hand would result in both moderate NO_x emissions and exhaust temperatures. So, using this approach and combining it with an aftertreatment system appears to be most reasonable.

More challenging than a steady operating point as described above is a transient one, so FEV also conducted different warm and cold runs according to WHTC.



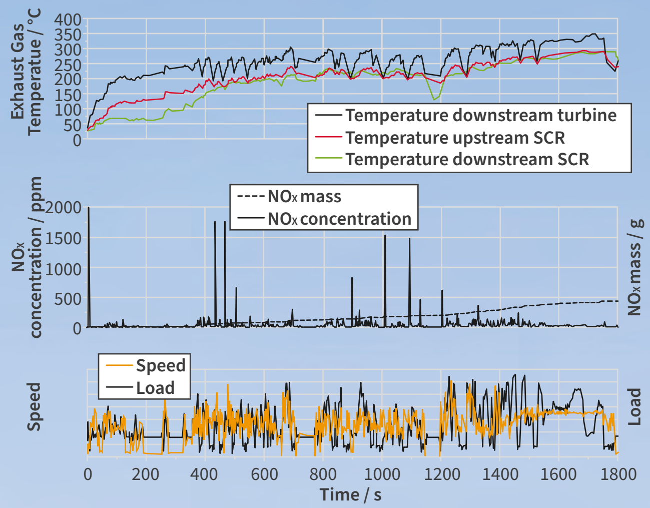
① *Comparison of the specific NO_x emissions and exhaust gas temperature downstream turbine depending on air/fuel ratio and on center of combustion*



② *Comparison of the exhaust gas temperature downstream turbine and the engine out NO_x emissions in WHTC for different air/fuel ratios*

As Figure 2 shows, the exhaust gas temperature difference between the runs amounts 20 °C to 50 °C. While there is an advantage in exhaust gas temperature, the worsened air/fuel ratio increases NO_x emissions 3.5 times.

The transient tests also revealed high NO_x peaks. The reach more than 5,000 ppm (parts per million) at $\lambda = 2$ (compared to just 50 - 250 ppm at steady conditions) and over 2,000 ppm at $\lambda = 2.3$ (compared to 10-40 ppm “steady”). For catalyst operations, the lower engine out NO_x emissions can be considered to be more beneficial than a temperature increase. Thus, the air/fuel ratio of 2.3 was chosen for the aftertreatment system tests, namely of those concerning selective catalytic reduction (SCR).



③ *Exhaust gas temperatures and engine out NO_x emissions for cold WHTC*

Warm-up with a Catalyst

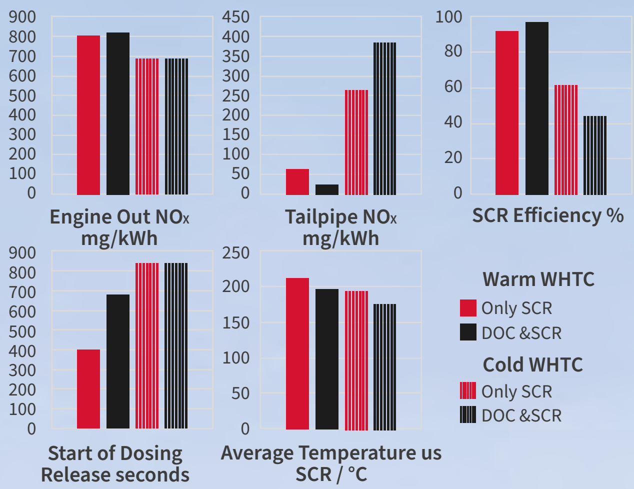
The heat-up phase poses the major challenge for the hydrogen combustion engine to reach near-zero-emissions.

The next FEV measurements (see Figure 3) were done with only an SCR installed. Heat-up time until dosing release is approximately 600 seconds. There are possibilities to overcome this phase and reduce the NO_x emissions already at those low temperatures, for instance: engine heat up modes, electrical exhaust gas heating or a passive NO_x storage catalyst (NSC). The latter collects NO_x during the heat up – and releases it thermally as soon as the SCR is warm and able to reduce these emissions.

To first investigate, how an SCR fits the hydrogen combustion engine in general, FEV compared two different set-ups: the SCR-only configuration and its combination with a Diesel Oxidation Catalyst (DOC), mainly to increase the NO_2/NO_x ratio upstream the SCR. This improves the NO_x conversion especially at low temperatures. Figure 4 displays the results.

The engine out emissions are on a relatively low level (~0.8g/kWh) compared to CV diesels. Because the calibration was only optimized for warm operation, slightly higher air/fuel ratios occur during the cold start phase. There, the NO_x reduction is small. The tailpipe emissions in the warm cycle are very low for both configurations, reaching just 62 mg/kWh and 24 mg/kWh. The additional DOC increases the NO_2/NO_x ratio upstream the SCR, and therefore its efficiency level: The DOC-SCR combination reaches 97 percent compared to 92 percent of the single solution.

The cold cycle though leads to a different result: With both catalysts together, the tailpipe emissions are higher and the SCR efficiency is lower than in the SCR only configuration The dosing release starts almost 200 seconds later and the average temperature upstream SCR is 15 °C lower. In the warm cycle, the better NO_2/NO_x ratio was more beneficial than the faster heat up. But it has less advantage in the cold cycle. Even more important: The results of the cold WHTC show that – independently from a DOC – a further solution is needed in the heat up phase to achieve an H_2-ICE with near-zero emissions.



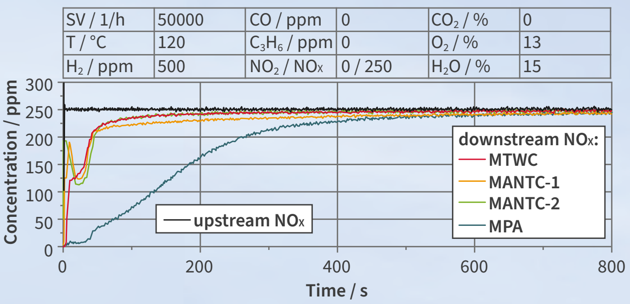
④ *Engine out and tailpipe NO_x emissions, SCR efficiency, start of dosing release and average temperature upstream SCR in warm and cold WHTC for SCR only and DOC&SCR aftertreatment configuration*

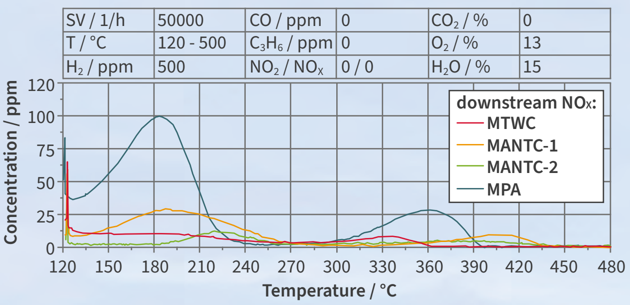
The NO_x Storage Catalyst provides a clean finish

This is where the previously mentioned NSC sets in. FEV performed concept simulations to analyze its effects on a lean operating hydrogen combustion engine. One target was to operate the NSC fully passive. This means that desorption should be ensured just by temperature. One first result: The exhaust temperature remains on a comparable high level at low loads. In most real-life operating cases, 300-350 °C will be reached.

A total four different catalyst samples (from Dinex) were analyzed to evaluate catalyst behavior in passive conditions: a "Modified Three-Way Catalyst" (MTWC), "Modified Active NO_x Trap Catalysts" in two versions (MANTC-1 and MANTC-2) and a "Modified Passive Adsorber" (MPA).

Gas bench analyses of all samples generated the input data (Figures 5 and 6) for the simulation model. It turned out that the adsorption behavior of the MTWC, the MANTC-1 and the MANTC-2 are very similar: They showed desorption at the beginning, and a strongly decreasing efficiency after just 20 seconds. The MPA adsorbs much longer with high efficiency. Also, its overall capacity and efficiency concerning NO_x storing is a lot better compared to the other three samples.





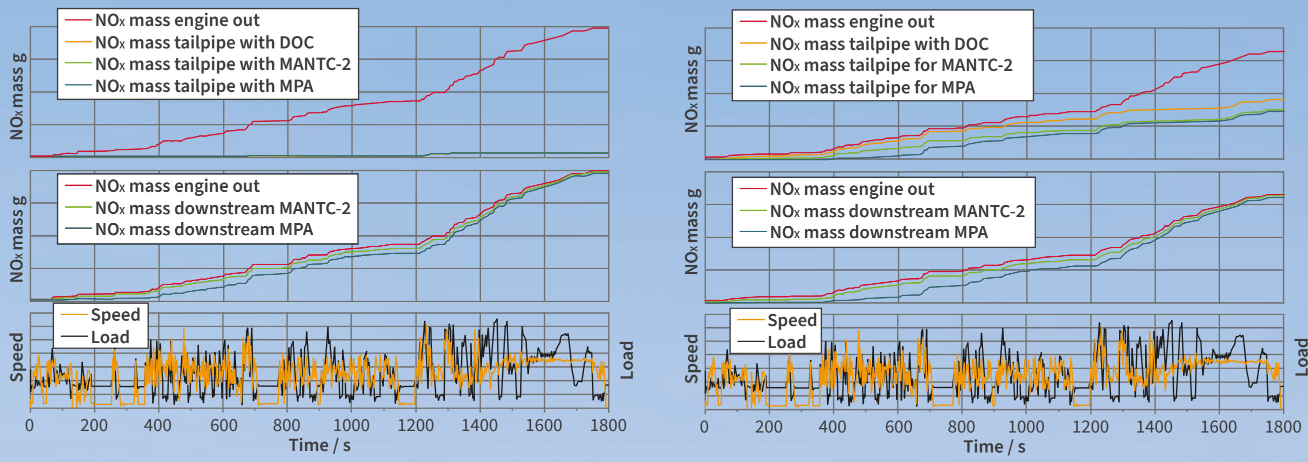
⑤⑥ *Adsorption of NO_x at 120°C (above) and desorption over temperature (below) for four different catalysts*

The MTWC desorbs most of the adsorbed NO_x before reaching 240 °C. And it has a second desorption peak at approximately 330 °C. The MANTC-1 desorbs most NO_x during a first peak at approximately 190 °C. The MPA reached the earliest, lowest peak here, namely at 180 °C already. The MANTC-2 in contrast desorbs later, at approximately 225 °C. Concerning hydrogen engines, it is also these two that offer the best potential for good results: The high storage capacity of the MPA is as beneficial as the late desorption of the MANTC-2. Therefore, both were used for the simulations.

These analyses were again performed for the warm and cold WHTC. At first, the DOC-SCR measurement was done during the warm WHTC for the following three configurations: without adsorber, with an MANTC-2, and with an MPA (see Figure 7). The impact of an NSC during such conditions is neglectable small, for both simulated catalysts. Because of the high SCR efficiency throughout this cycle there is no adsorber benefit, though no drawback too.

The findings for the cold WHTC instead do show a clear benefit for both simulated catalysts compared to the DOC-SCR-only measurement. They achieve similar tailpipe results: Using them can reduce NO_x emissions in this cycle from 385 mg/kWh to 320 and 309 mg/kWh. Those lead to a reduction of the weighted results from 75 mg/kWh to 65 mg/kWh respectively 64 mg/kWh. The average DeNO_x efficiency for the cold WHTC rose – from initially 44 percent – to 54 percent for the MANTC-2 and to 55 percent for the MPA.

The SCR calibration was optimized not for the highest, but for high efficiency without any considerable NH_3-slip. Especially when a slip catalyst is not part of the aftertreatment concept to avoid the N_2O formation, the heat up phase becomes a major challenge. A passive NO_x adsorber is able to help reduce emissions.



⑦⑧ Cumulated NO_x masses for a warm (left) and cold (right) WHTC, each compared without adsorber, with a MANTC-2 and with a MPA (simulations)

The outcomes furthermore reveal a strong dependency between NO_x emissions, exhaust gas temperature and air/fuel ratio. This offers a high potential for calibration optimization with respect to the status of the aftertreatment system. Developing a hydrogen combustion engine as a near zero emission powertrain also requires the alignment of combustion and aftertreatment during design, calibration and operation.

Summary and Outlook

To continuously improve the H_2-ICE as an alternative to battery electric or fuel cell powertrains, the pollutants need to be at very low levels. FEV simulations show: Combining a passive NSC with an SCR enables that. Further steps are necessary to validate this concept as a suitable solution under real and ambient conditions. The ageing under high water concentration needs to be investigated in more detail. Further analyses are required for a possible NSC temperature control to avoid any need for active purging.

An accurate dosing control including correction functionalities in case of inaccuracies or drifts is also necessary. Existing solutions might therefore need improvement or extension. Sensor accuracy needs to rise too. That can reduce both the risk of NH_3 slip and the need for an ammonia slip catalyst that might form N_2O – a pollutant that needs to be avoided in general. Soot particulates, potentially caused by burnt lubricant oil in the combustion chamber, could occur at very low levels. Nevertheless, that might raise the question whether a particulate filter is needed.

But even if not all aftertreatment system possibilities have yet been exploited down to the last detail: The H_2-ICE proves to be good and sensible even today, especially for long-distance trucks and for off-road applications. There, manufacturers are planning early market launches accordingly. The hydrogen combustion engines announced for 2023 and 2024 will, with only a little fine-tuning, thus already be very clean.

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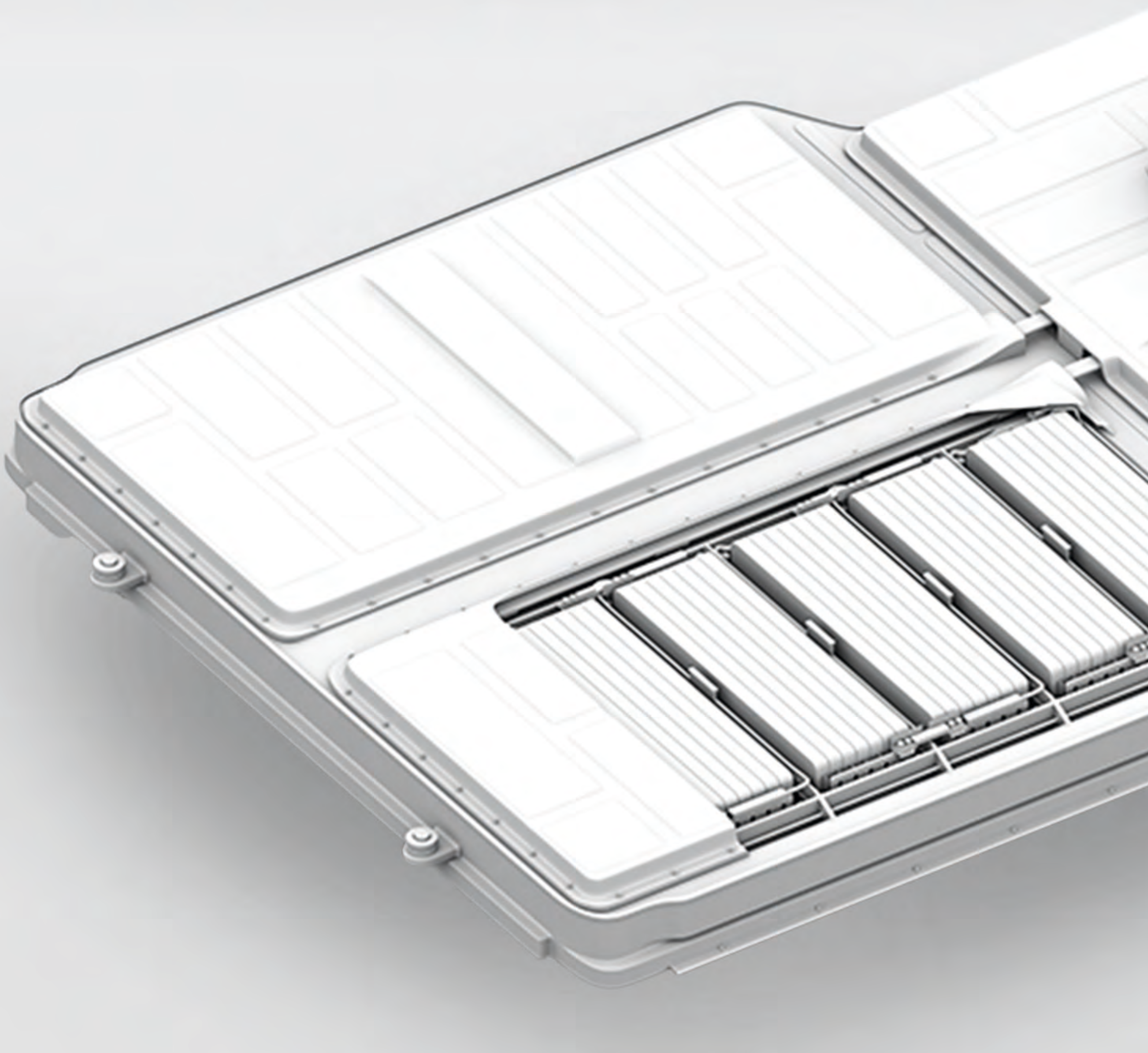
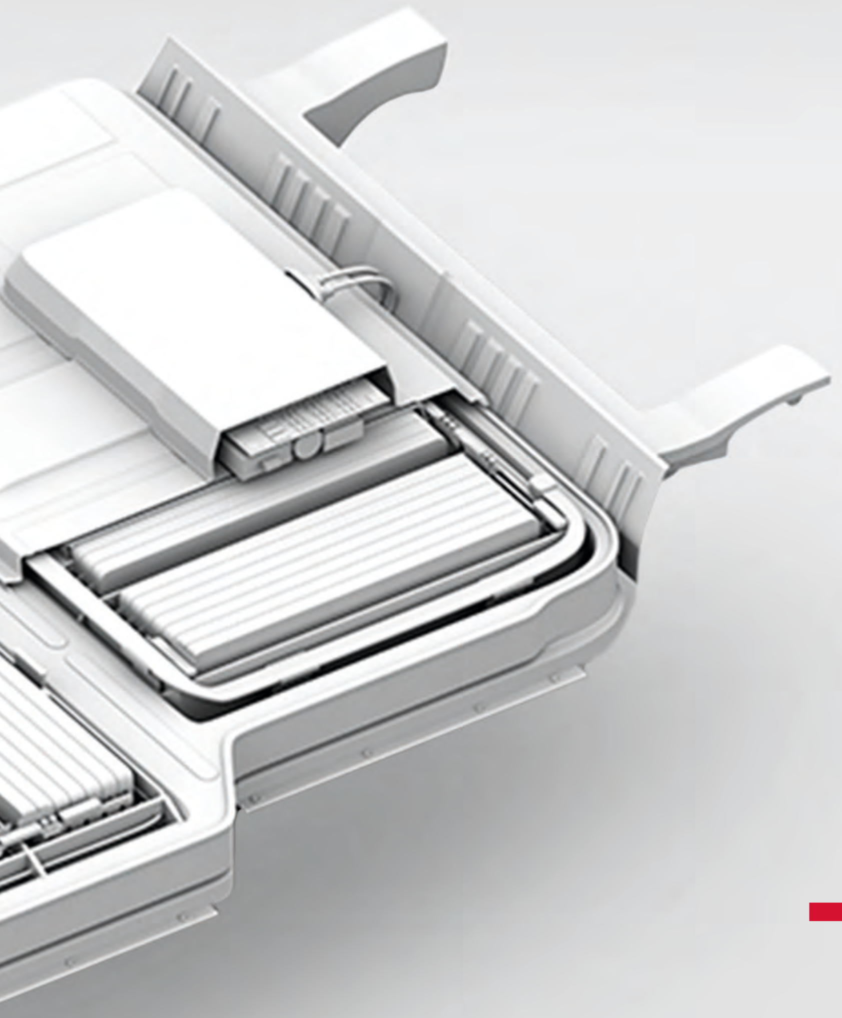
ELECTRIC VEHICLE POWER STORAGE

FEV SPANS BATTERY MEGATRENDS FROM MATERIALS VARIETY OVER SAFETY TO ENERGY DENSITY

Electric cars are essential for the required defossilization of mobility, with Lithium-ion batteries being the cutting-edge technology for electrification. To gain wide acceptance, they need constant improvement. This involves, for example, increased energy density and faster charging speeds. At the same time, the higher energy content must comply with the increasing safety standards. So, which are the promising new approaches for improving battery characteristics, what screws can be adjusted on cell, system, and vehicle integration level? FEV has answers.





Today, there is a largely common understanding that electrifying road transport is essential for reaching future CO_2 targets. The battery electric vehicle (BEV) plays a main role in this transformation. Its success largely depends on the energy storage on board: Mainly the battery decides the car's range, price, and weight. It also strongly influences the vehicle's performance both on-road and during charging. As a consequence, the industry works with full power on new cells and chemistries to enable batteries with much higher energy content. At the same time, they must contribute to meet increasingly stricter safety levels. Batteries could even become an integral part of a vehicle's chassis. FEV now analyzed current and future technologies as well as development approaches on battery cell and pack level.

Battery cells become diverse

As materials and cells are getting cheaper, the costs of batteries could decrease faster than predicted. Additionally, vehicle requirements like range and charge time progressed strongly over the recent years. The selecting and matching of materials towards each other together with optimizing and finetuning cell production are major levers to influence the battery cell's most important characteristics, for instance: its safety, sustainability, costs, cycle life, energy content, and power capability. Many of these criteria are majorly influenced by the cathode materials. And these account for almost 40 percent of the raw material prices of a battery cell.

Historically, Lithium Cobalt Oxide ($LiCoO_2$ or LCO) was used due to its high-performance capabilities. Amongst other factors, questionable mining conditions and price increases due to little availability led to the alternative use of Lithium Nickel Oxide ($LiNiO_2$ or LNO). The drawbacks of this material (see Fig. 1) are often mitigated by partially substituting LNO with Cobalt.

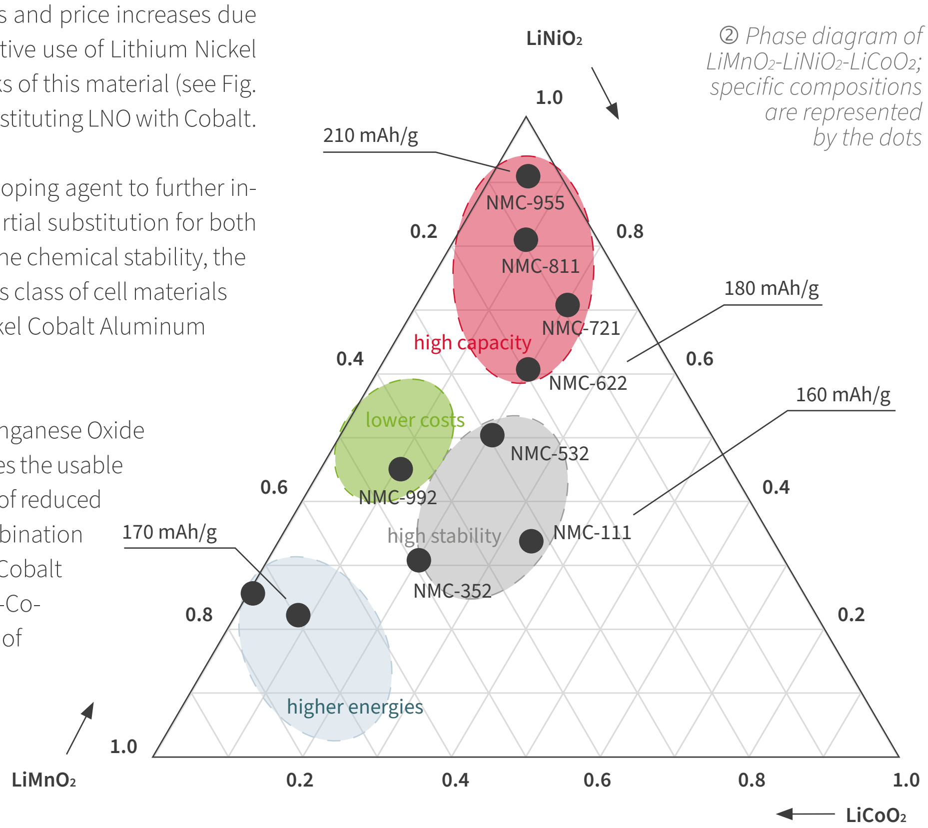
Furthermore, Aluminum is used as doping agent to further increase the chemical stability. As a partial substitution for both Nickel and Cobalt, it could improve the chemical stability, the cycle life, and the energy density. This class of cell materials is better known as NCA (Lithium Nickel Cobalt Aluminum Oxide).

LNO can also be substituted with Manganese Oxide ($LiMnO_2$ or LMO). That mainly increases the usable operating voltage, with the drawback of reduced stability and thus cycle life. The combination of doping with both Manganese and Cobalt called NMC (Lithium-Nickel-Mangan-Cobalt-Oxide,) allows the optimization of the cathode properties and made this class of materials the most used. Figure 1 summarizes some high-level properties:

(Re)Searching for the all-in-one material solution

The effects and correlations in between these materials are depicted in Figure 2. The cathode chemistries currently under development (e.g. NMC-811, NMC-955) offer high discharge capacities but also exhibit lower cycle stability and reduced thermal stability.

New future material combinations are expected to lead to further diversification. This includes more elaborate iterations of NMC materials and different chemistries. Lithium-Iron-Phosphate

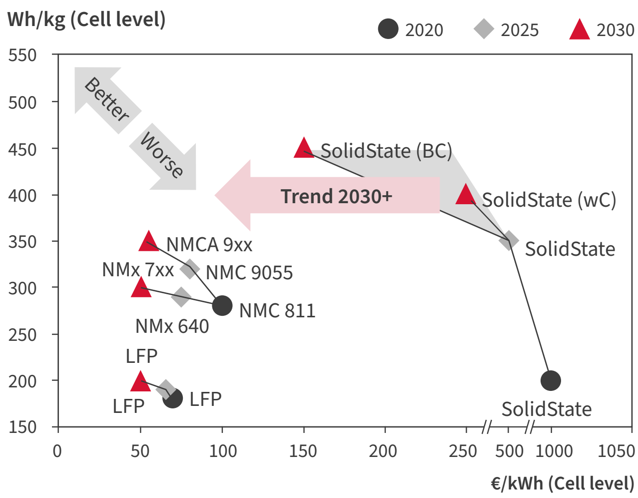


② *Phase diagram of $LiMnO_2$-$LiNiO_2$-$LiCoO_2$; specific compositions are represented by the dots*

	ADVANTAGE	DISADVANTAGE
LNO ($LiNiO_2$)	Discharge capacity	Lower thermal stability, cost increase in the mid-term, reduced stability at high states-of-charge
LCO $LiCoO_2$	Discharge rate, stability	Costs, availability, environmental impact
LMO ($LiMnO_2$)	Operating voltage, costs	Cycle stability, lower capacity than Ni

① *Very simplified, main characteristics of LCO, LNO, and LMO; Boundary conditions such as stability of the crystal structure are not shown*

(LiFePO4, LFP) combines important features: It is chemically and thermally stable and allows for high discharge rates, but at the cost of low discharge capacity. Yet, today's LFP battery cells already surpass last decade's high-energy NMC cells. LFP batteries are being employed as low cost and safe energy storage in systems which do not have the highest range priority – like public city buses. Figure 3 provides both an overview of different cell chemistries and an outlook until 2030.



③ *Overview of the energy density (gravimetric) of cell chemistries in Wh/kg over costs per kWh*

As it can be seen, NMC based battery cells are very much trimmed towards high discharge capacities by increasing foremost the Nickel content, using SiOx anodes and improved production. The cost is reduced primarily by the wide introduction of mass production, however, also by using less Cobalt. A price increase for Nickel raw material can already be observed which is expected to increase drastically over the next years as battery mass production ramps up even more. Therefore, the development already shifts away from increasing only the Nickel towards increasing Manganese content in the cathode material. These materials are expected to enter the market within the next years.

The solid-state future remains uncertain

The revolutionary solid-state battery technology aims at employing lithium metal in combination with a high energy cathode material and a solid electrolyte/separator. But still, they face major challenges: The hurdles range from mass production of proven chemistries over cold temperature performance to in-depth swelling investigations on the mostly used pouch cells on system level. A mass produced, all solid-state battery cell is therefore not expected to enter the market at a competitive price before 2030, despite singular breakthrough announcements.

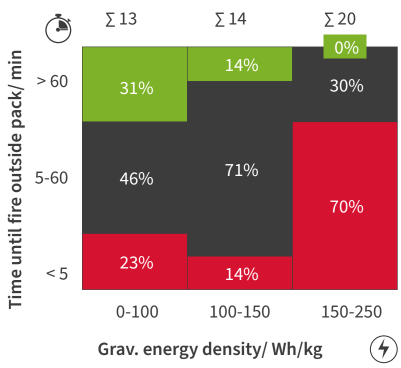
But NMC materials further developed towards high energy densities are challenging too; Nickel rich layered oxides generally reduce the structural and thermal stability, especially at high states of charge. On system level, this indicates a reduced cyclic lifetime and an earlier onset of potential thermal runaway chain reactions. An example: The conventional material remains stable even at temperatures of 300°C and more, the new one (NMC-622) decomposes already above 270°C. Because these materials increase the energy density of batteries and thus the BEV range, such restrictions are accepted though. So, maintaining or improving safety on cell and system level becomes more demanding.

FEV insights in safety for high energy batteries

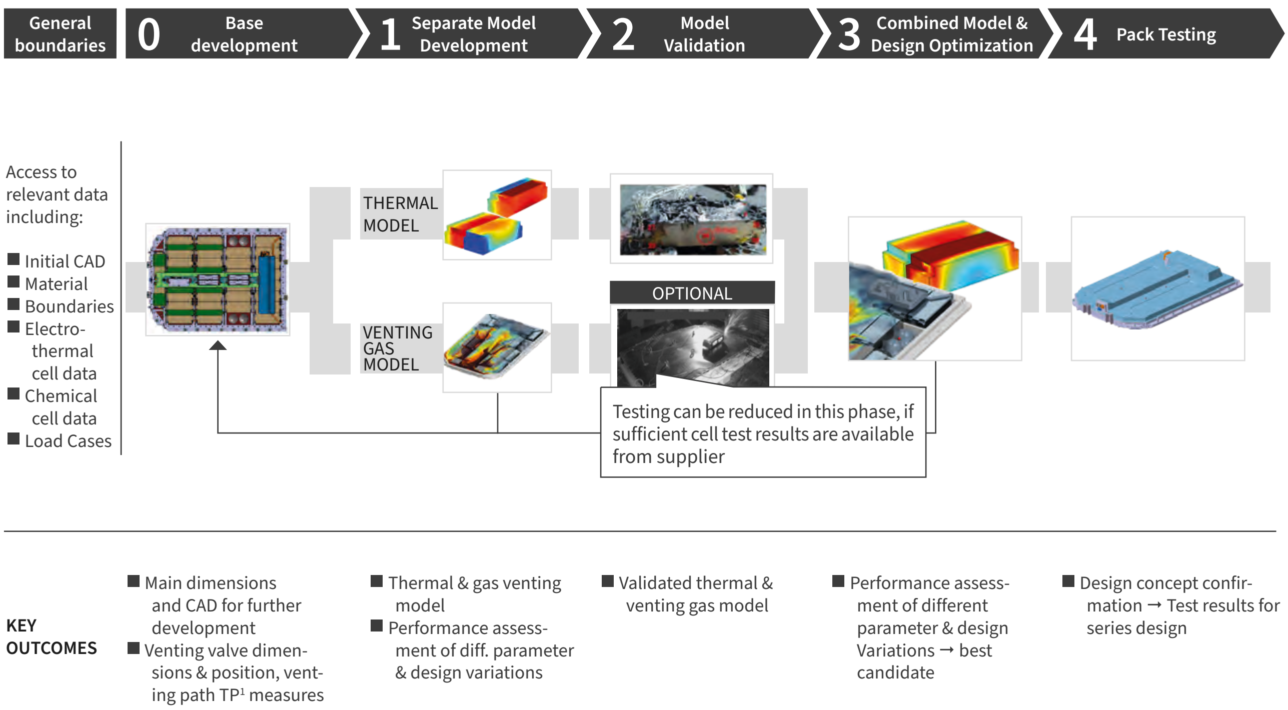
Concerning safety, the currently strictest homologation rules are ECE R100 (revision 2) in Europe and GB 38031 in China. The latter imposes two new requirements regarding potential thermal events in high voltage (HV) batteries: At first, warning signal must alert passengers. Secondly, a five-minute period must be allowed during which no passenger must be harmed. This is usually interpreted as no fire outside of the battery housing. These rules will also be adopted into the ECE R100 in the following years. Furthermore, it is expected that the mandatory time limit will later gradually rise to 20 or even 40 minutes. The ultimate goal, of course, is no fires outside a battery.

To certify a battery system according to these legal requirements, its development status needs to be validated already at early stages. FEV's modern battery test facility eDLP manages that task: It has several test sites which are designed for abuse testing of cells, modules, and packs. Figure 4 summarizes results from pack-level thermal propagation tests.

The tests to date reveal that across all energy density classes there are batteries that do not fulfill the 5-minute criteria. This number is drastically higher for the category "above 150 Wh/kg". Many batteries though can keep a thermal runaway internal for 5 to 60 minutes, most of them are from the "middle class". Almost one third of base category batteries keep a fire inside for even more than one hour (green fields in Figure 4), but zero from the analyzed top-class representatives. So, the higher the energy content, the more challenging it becomes to completely contain a thermal runaway within.



④ *Thermal runaway tests results of battery packs with differing gravimetric energy densities*



⑤ *FEV development approach for highest thermal safety of automotive battery systems*

Saving months in battery development

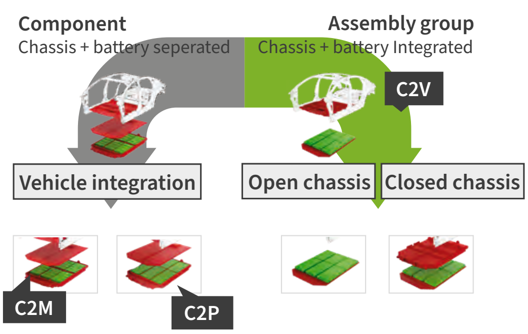
The field proven FEV approach to handle the high priority topic “safety development” consists of four steps (see Figure 5).

After the first base battery design, two separate models are usually developed (step 1): a detailed 3D thermal model and a dedicated venting gas model. In step 2, a model validation is encouraged to maintain high accuracy and confidence in the simulation results. Afterwards, the models are combined to simulate thermal propagation events on pack level. If required, more details are added such as particle flow and/or flame propagation. This output is then used for design optimization (step 3). Multiple iterations can be done in order to achieve the best possible result, for example regarding the position and thickness of heat barriers. Pack testing itself is only step 4 and ideally requires very few battery packs. In total, FEV’s simulative approach reduces development time by several weeks or months – and thus costs too.

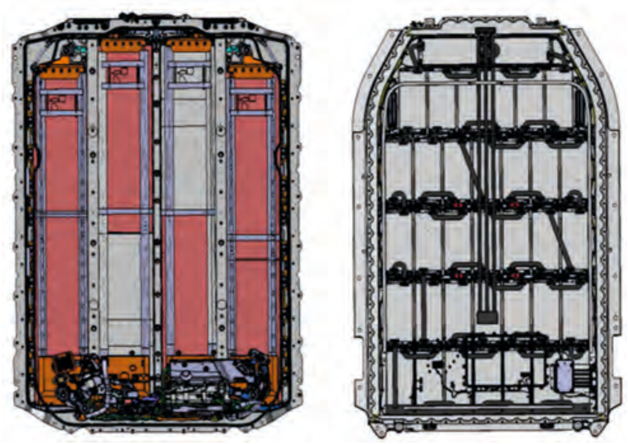
Vehicle engineering to improve battery characteristics

A different approach to improve BEV characteristics is optimizing the integration of the battery cell into a vehicle (cell-to-vehicle, C2V) and into the pack (cell-to-pack, C2P): The latter means improving the pack as a component, build independently from the vehicle until the integration. Modules and housings are omitted as much as possible. This approach allows to save weight and space. The classic approach with modules is called cell-to-module (C2M) design and relies largely on the same concept: C2P is an optimization of C2M. A high-level classification is shown in Figure 6. C2V is a novel concept which reevaluates the integration of the battery pack into the parent vehicle: the battery pack is not necessarily a standalone component anymore but an assembly group of the chassis. This means that a decision to build a battery electric vehicle using a cell-to-vehicle approach is much earlier within the entire value chain and development process and thus affects larger parts of the value chain.

The battery also potentially adds to the vehicle’s structure: For example, the crash, crush, and vibration mitigation structures can either be mostly located in the chassis (e.g. Tesla Model S), or functions can be transferred and/or added to the battery (e.g. Mercedes EQC).



⑥ *Classification of cell-to-module, cell-to-pack, and cell-to-vehicle concepts*



⑦ *CAD models of a Tesla Model 3's (left) and a Jaguar I-Pace's battery pack (right); The top view with removed cover is shown (driving direction: from bottom to top)*

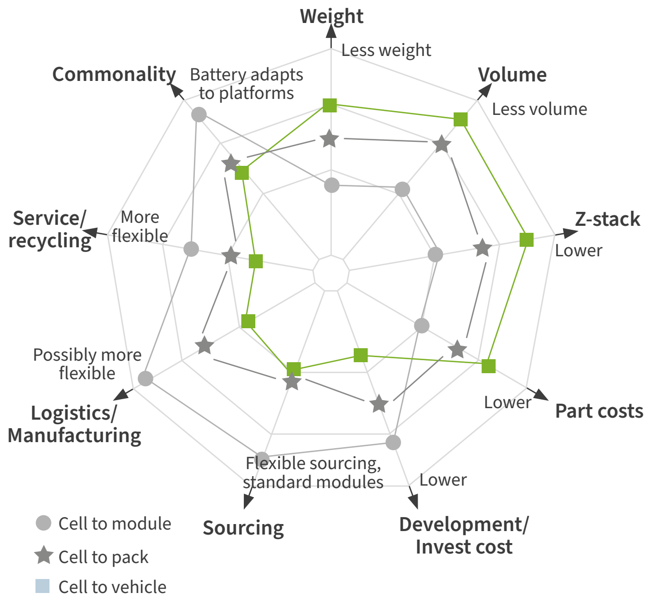
To further evaluate C2P and C2V concepts, FEV investigated these approaches theoretically by applying them to CAD models from a Tesla Model 3 and a Jaguar I-Pace (Figure 7).

Figure 8 highlights the most important findings. Interestingly, the possible increase in volumetric energy density is higher than the increase in gravimetric energy density. Furthermore, the reduction in z-height has the potential to impact the overall design and to open new packaging opportunities.

	CELL-TO-PACK	CELL-TO-VEHICLE
Flexibility / communality Parts which can be exchanged/serviced. Fewer indicate less flexibility and more effort to achieve communality over platforms	90%	75%
Overall costs Development and parts costs combined	95%	70%
Energy density – volume Recalculated values due to reduced volume	135%	150%
Energy density – weight Recalculated values due to reduced weight	113%	120%
Z-stack Space savings in z-direction, one of the most critical development targets	-15 mm	-22 mm

⑧ *High-level results of implementing a C2P and C2V approach in the Tesla Model 3 and Jaguar I-Pace battery pack, given as mean qualitative value*

Sticking to modules remains the more flexible, service and recycling friendly approach. Furthermore, the communality in between multiple platforms can be high, e. g. in the Volkswagen MEB platform. Logistics and vehicle production are already established. The sourcing potentially offers higher flexibility, as manufacturers can get standard module sizes from multiple suppliers. Even using different cells in the same battery pack design is possible.



⑨ *Spider plot of three battery integration concepts; Figure shows FEV's assessment of the different approaches*

However, this flexibility negatively impacts battery weight, volume, and height. That can be improved by using a challenging C2P battery or by going for a C2V approach (see Figure 9). Opting for a such a high vertical integration of body and battery also puts more emphasis on the battery cell selection. Thus, the cell and its characteristics impact the overall development even more.

The one and only future battery design- and integration concept that improves everything has not been invented yet. But there are many new opportunities to optimize batteries for each demand and use case. A small startup, for example, has other requirements than a large OEM. There are constants though: For new BEVs, the battery system remains at least as important as before; and FEV knows exactly how to take that into account best.

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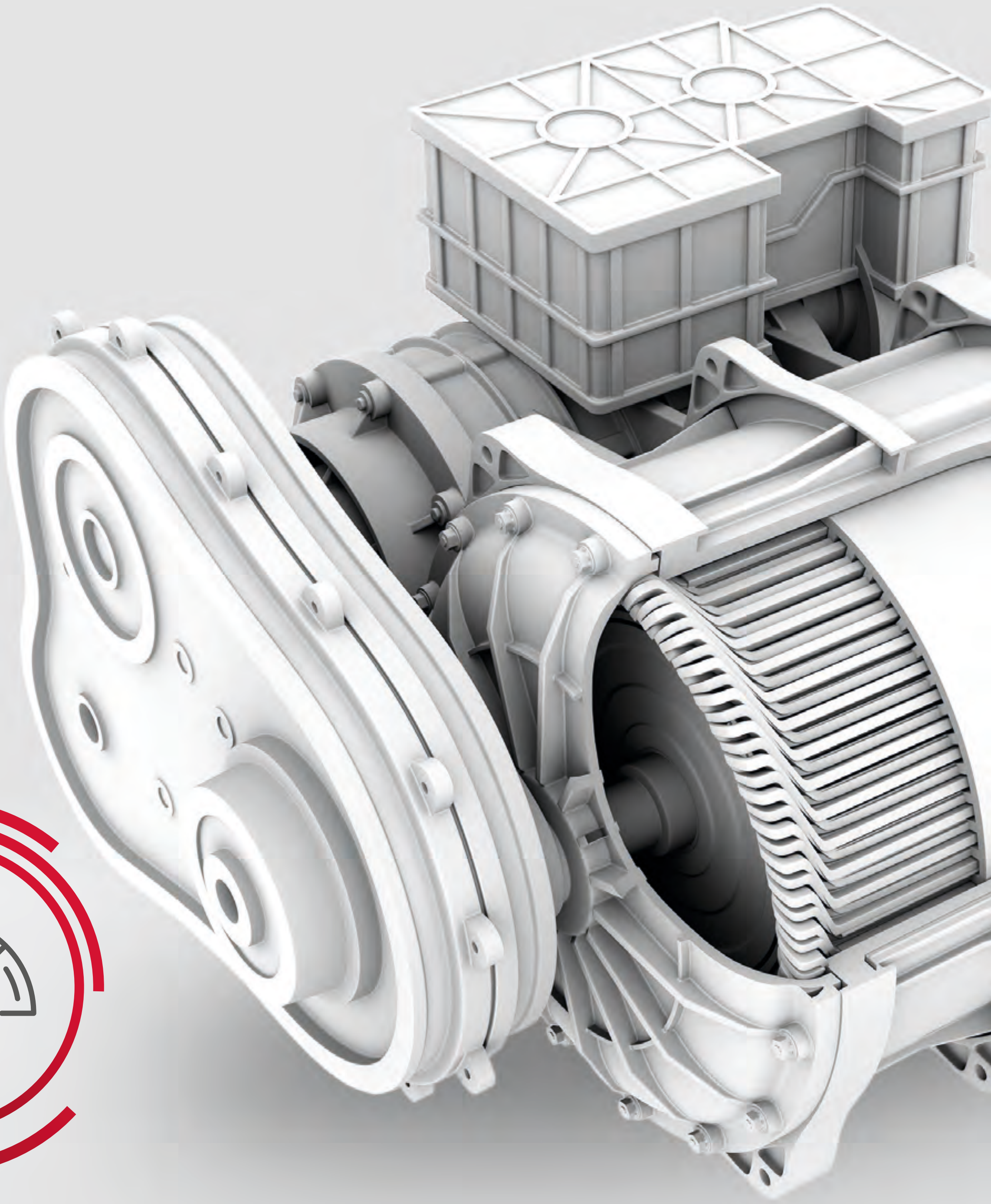
E-MOTOR POWER SAVING STRATEGY

FEV STRENGTHENS ELECTRIC CAR EFFICIENCY BY THERMAL FIELD WEAKENING

Reduced energy consumption and increased vehicle range? Also in electromobility, higher drivetrain efficiency is the key. FEV's new thermal management approach for the most common electric motor topology can quite easily reduce energy consumption by up to one percent. For upcoming electric motor generations, the potential of this strategy is much higher.



An electric vehicle's (EV) motor does already offer a high efficiency, but it also significantly contributes to the remaining drivetrain losses. FEV has therefore developed a new approach to improve the status quo of permanent magnet synchronous machines (PMSMs), the currently most common choice for electric vehicles. This strategy is called "active thermal field weakening".

With the magnet temperature, the range can rise

Due to high power and torque requirements, such as fast acceleration, and the design for peak power, rare earth permanent magnets with high magnetic energy densities are used in PMSMs. These magnets have a high inherent magnetic excitation. The magnetic excitation cannot be adapted to different operating points, as it would be the case for externally excited synchronous machines or induction machines. For this reason, in permanent magnet synchronous machines, to achieve higher speeds, an additional current must be injected in the field weakening area, which generates a magnetic field opposite to the permanent magnets in order to weaken their excitation. This additional current increases the copper losses, which has a negative effect on the efficiency of the electric machine. In addition, only a small part of the possible operating range of the machine is used in day-to-day driving. Operating points with the highest torque and power requirements are only needed in a few exceptional situations.

To be able to vary the magnetic excitation, FEV therefore takes advantage of a characteristic property: Due to the negative temperature coefficients of remanence flux density and coercivity, the magnetic energy density of rare earth permanent magnets decreases with increasing temperature. This behavior can be used in the field weakening range, at operating points with lower power, to increase the rotor temperature and thus also the magnet temperature. With reduced cooling power, the permanent magnets are thus already thermally weakened. This means that only a small amount of additional current is required for field weakening, which reduces copper losses at these operating points. Consequently, active thermal management – implemented via an alternative cooling strategy – can be very well suited to regulate magnetic excitation. In other words, if the temperature can be increased in a controlled manner at operating points with low loads, the electric motor gains overall efficiency.

FEV studies have shown that this reduces energy consumption by 0.32 percent in a real-world driving cycle (designed by FEV) and by 0.59 percent in the worldwide harmonized light vehicles test cycle (WLTC) for class 3 vehicles. At a cruising speed of 120 km/h, energy consumption is reduced by about one percentage point compared with an electric motor with a conventional cooling system.

Which car was simulated?

The FEV simulation and analyses are based on a compact electric vehicle, powered on one axle by a PMSM with 150 kW and 310 Nm. This setup represents current series production EVs. The detailed vehicle and machine parameters are shown in Figures 1 and 2. To match the moderate power level, 400 V was defined as the system voltage. For the inverter, FEV assumed a system with power semiconductors based on silicon carbide (SiC).

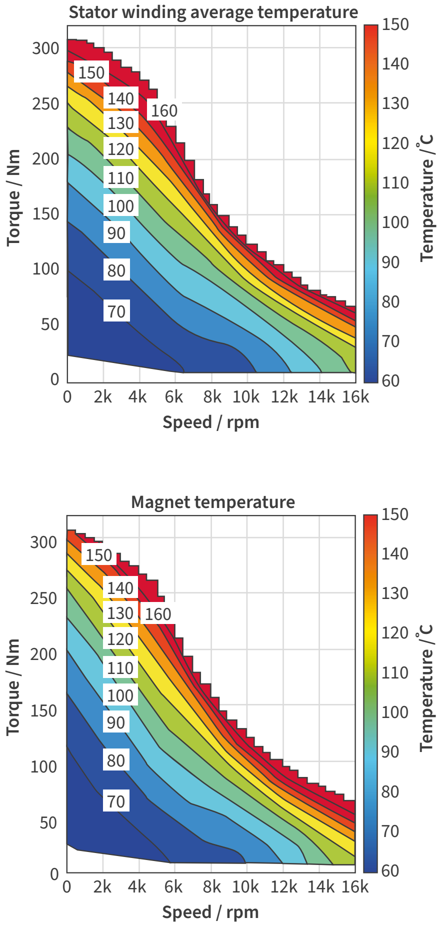
Parameter	Value	Unit
Curb weight	1.850	kg
Gross vehicle weight	1.925	kg
Frontal area	2,36	m^2
Drag coefficient	0,267	–
Maximum vehicle speed	160	km/h

①②: *Vehicle parameters (top) and electric machine parameters (bottom)*

Parameter	Value	Unit
Peak power	> 150	kW
Peak torque	310	Nm
Maximum effective current	450	A
Electric torque constant	0,63	Nm/A
Rated voltage	355	V
Rotor diameter	161	mm
Active length	230	mm
Maximum speed	16.000	min^{-1}
Number of slots	48	–
Number of pole pairs	4	–
Electrical steel sheet for rotor and stator	M235-35A	–
Permanent magnet material	N42UH	–

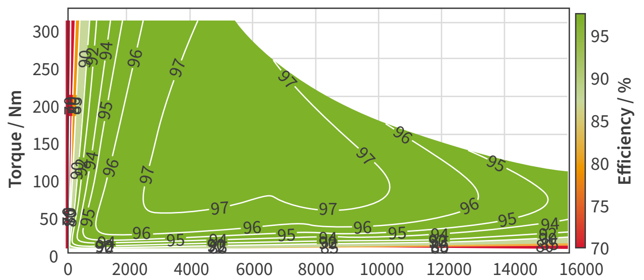
Figure 3 visualizes the average winding temperature in the stator (above) and the magnet temperature (below) as a function of the operating points in the torque-speed map. The temperatures are obtained in thermal steady state condition, at a nominal coolant inlet temperature of 60 °C and a coolant flow rate of 10 l/min. The electric machine is rather cool over large parts of the operating range. The magnet temperature remains below 100 °C up to a continuous power of 50 kW at around 10,000 rpm.

The operating point dependent efficiency is shown in the efficiency map in Figure 4, for a rotor and stator temperature of 60°C. There is a large area in which an efficiency of 97 percent



③ *Average winding temperature in the stator (above) and magnet temperature (below) as a function of the operating points in the torque-speed map at a nominal coolant inlet temperature of 60°C and a coolant flow rate of 10 l/min*

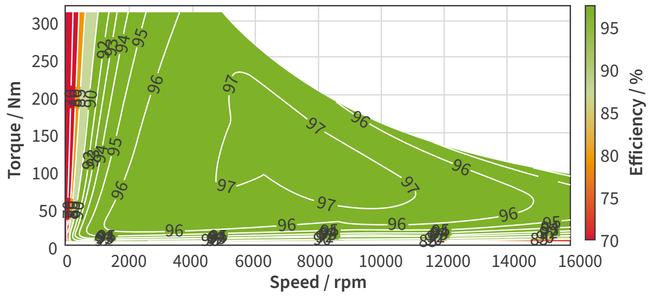
is achieved. The range with an efficiency above 95 percent ends approximately at a speed of 15,000 rpm and 75 Nm torque. At very high speeds and simultaneously low torques, a small range can be identified in which the efficiency drops below 85 percent. This is shown in yellow and red in the efficiency map.



④ *Efficiency map for a rotor and stator temperature of 60 °C.*

Temperature dependence of the efficiency

The efficiency map of the PMSM shown in Figure 5, shows how the operating point-dependent efficiency changes with increasing temperature.



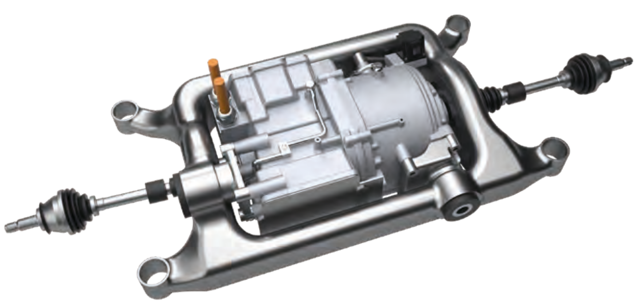
⑤ *Efficiency map for a rotor and stator temperature of 140 °C*

The efficiency map at 60°C in Figure 4 showed a range of 97 percent extending to the corner point at approx. 5500 rpm and 310 Nm. However, with increasing temperatures, as shown in Figure 5, the efficiency decreases for this corner point. So, for these operating points with a high power, good cooling is necessary in order to achieve high efficiencies.

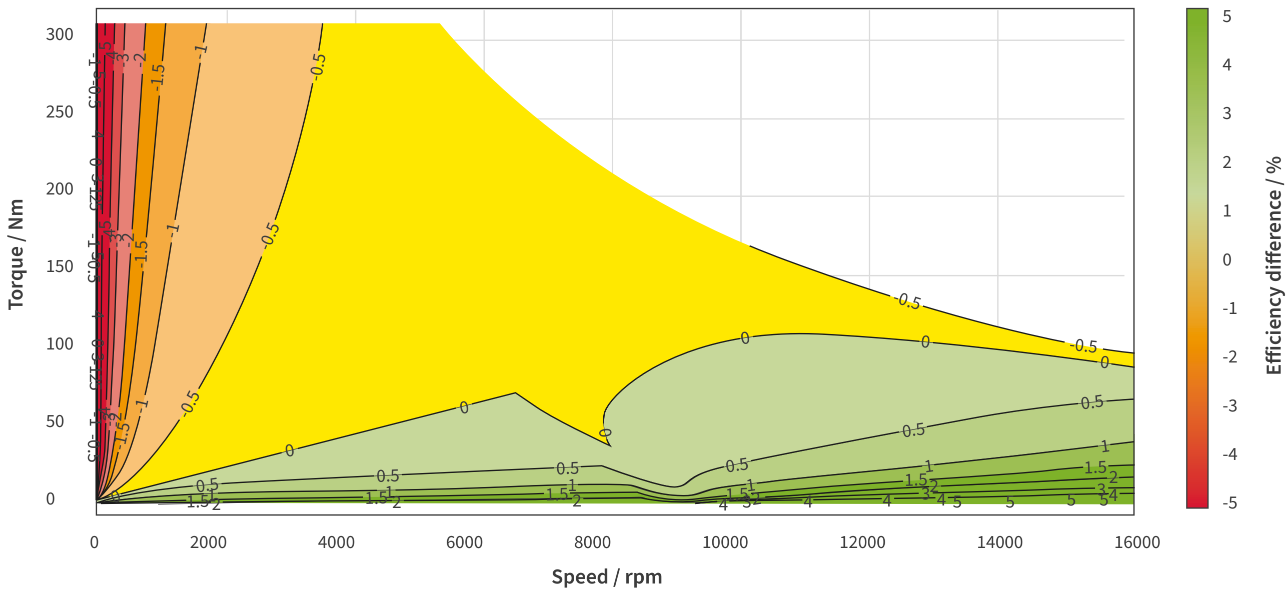
This behavior is exactly different for regions with lower power. For torques below 100 Nm, the range in Figure 4 with an efficiency of 97 percent at 60 °C extends from about 2500 rpm to just over 10,000 rpm. However, at a temperature of 140 °C, as shown in Figure 5, this range with an efficiency of 97 percent extends to over 11,000 rpm. In general, the efficiency at 140 °C at high speeds and at low torques exceeds that at 60 °C. The range of only a maximum of 85 percent efficiency (again shown in yellow and red) is also significantly smaller than at a rotor and stator temperature of 60 °C.

Identifying new thermal possibilities

FEV investigated in more detail the benefit of higher temperatures in some operating ranges. Especially when it comes to improving the overall efficiency over complete driving cycles and thus increasing the range of the electric vehicle, the temperatures in the electric machine as part of the overall powertrain play a decisive role. An example of such a powertrain for an electric vehicle is shown in Figure 6.



⑥ *Exemplary drive train of an electric vehicle*



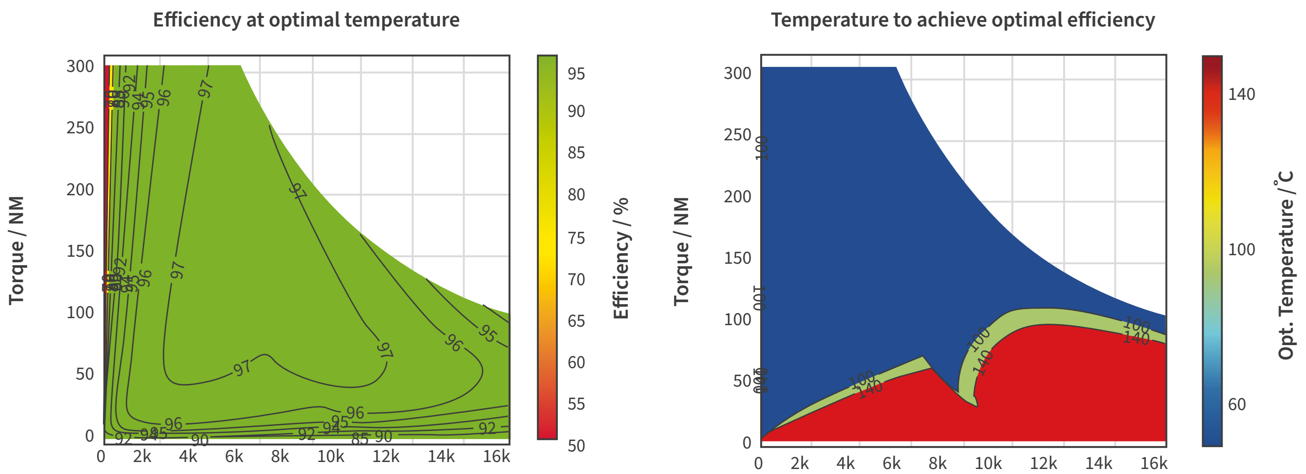
⑦ *Increase or decrease in efficiency when the motor temperature is increased from 60°C up to 140°C*

FEV therefore analyzed the potential for operating the motor at a higher temperature for different operating points. Figure 7 illustrates how efficiency changes when the entire electric machine is heated from 60 °C up to 140 °C. The positive values describe higher efficiency at a high temperature and the negative values describe reduced efficiency at a high temperature. At 10,000 rpm, a higher motor temperature is beneficial for powers up to 100 kW. Lower temperatures, however, result in better efficiency at low speeds and high torques, since the temperature dependent electrical resistance decrease and hence the copper losses. Also, the higher magnet strength decreases the current required to reach a certain torque.

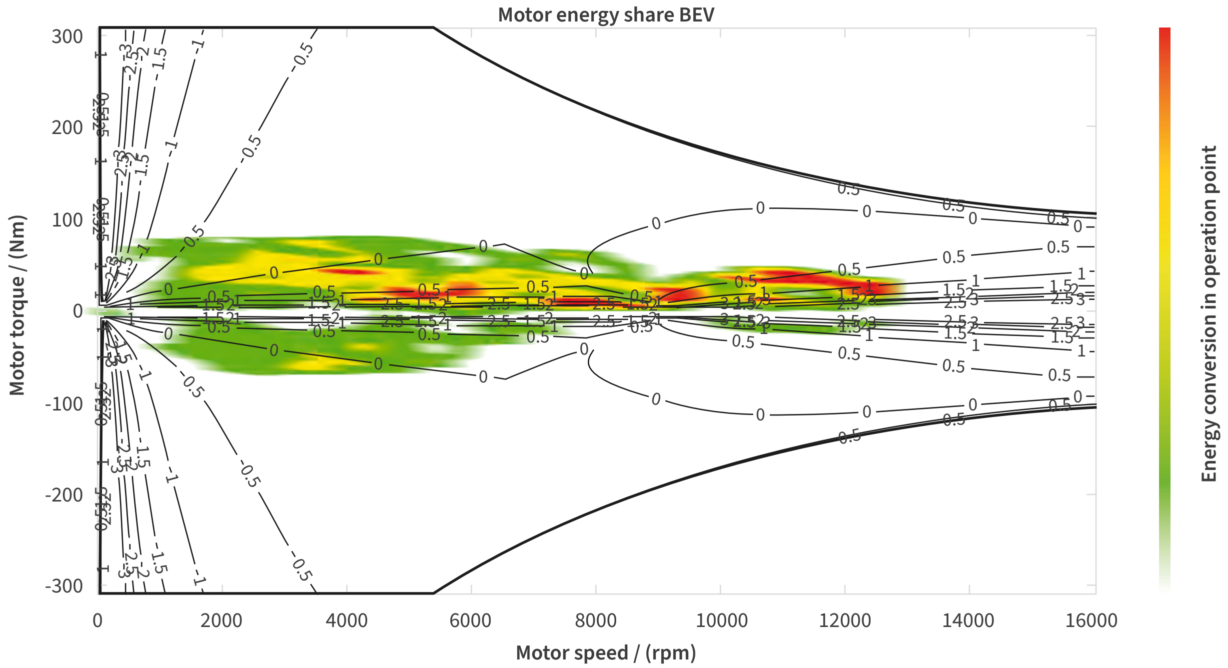
The combined efficiency map, shown in Figure 8 (left), is obtained if for each operating point the motor temperature is selected from which the highest efficiency results. Figure 8 (right) shows the required temperatures for each operating point, which must be achieved for the best possible efficiency.

One of the disadvantages of increased overall motor temperature is a reduction in maximum performance. At full-load acceleration – the peak torque and power area rarely used – a cooler electric machine offers higher torque and therefore better performance. However, Figure 9 shows that most energy conversion occurs at operating points where higher temperature is better. Shown is the operating point distribution that results for the simulated vehicle for a WLTC class 3 driving cycle.

This suggests that reducing the magnetic energy density by selectively increasing the temperature by active thermal field



⑧ *Combined efficiency map of the electric motor (left) and the required temperatures (right)*



⑨ *Energy share for operating points resulting for the simulated vehicle for a WLTC class 3 driving cycle*

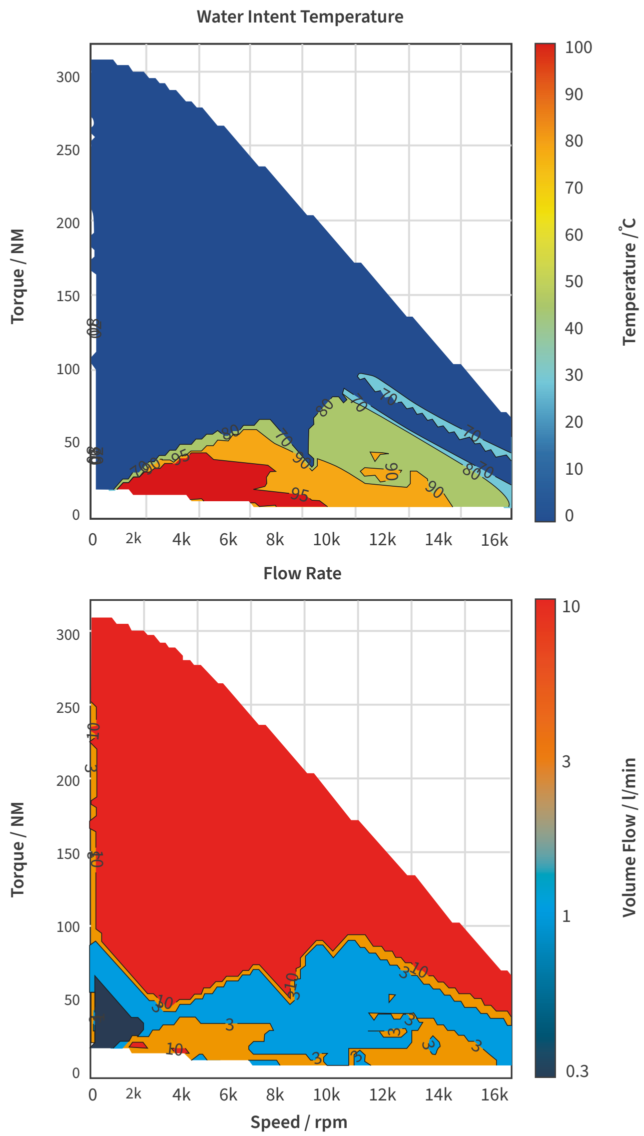
weakening, helps the electric car to be more efficient at most real operating points. Or, put simply, "hotter" is better for everyday driving. To further verify these findings, FEV applied the strategy described above to the EV drivetrain.

Taking the coolant into account

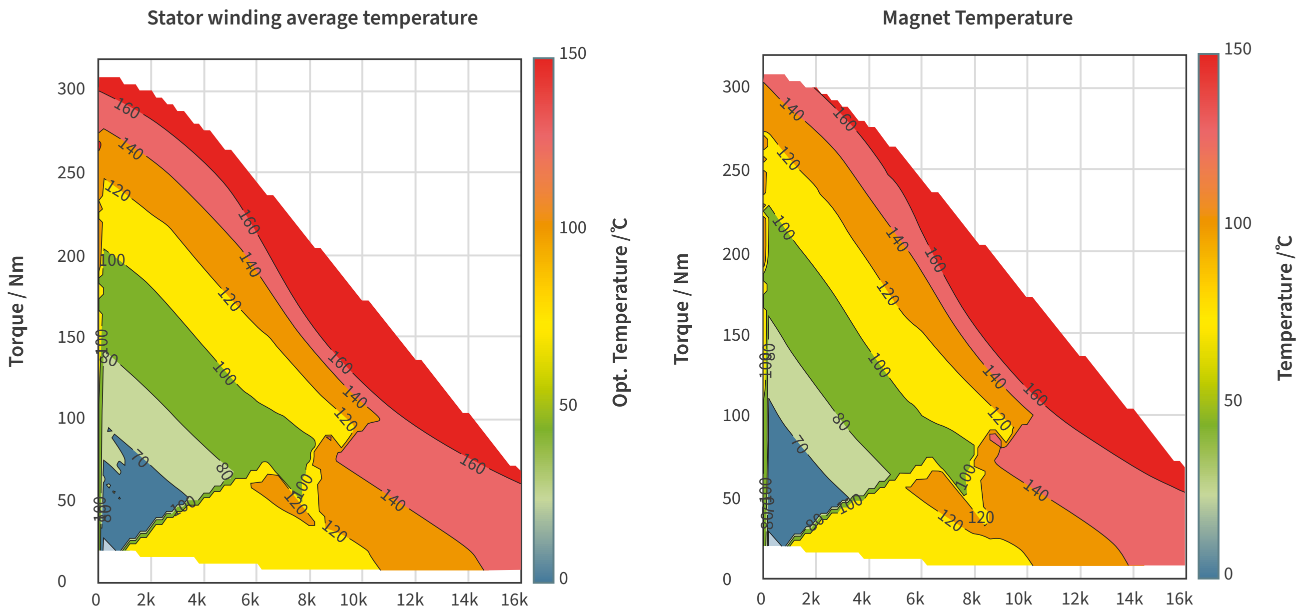
In order to raise the temperature of the PMSM to a higher level, it is important to understand how tem-perature management usually works. In the steady-state thermal condition, there are two influencing factors: the losses as well as the heat transfer to the coolant. In the case example of the electric motor with water jacket cooling and air-cooled rotor, the rotor and stator temperatures cannot be influenced separately. Based on the preferable temperature ranges from Figure 8 (right), FEV calcu-lated the neces-sary coolant inlet temperatures and flow rates shown in Figure 10.

For the target area of 60 °C, the desired inlet temperature is always 60 °C. The lowest temperatures are achieved for a high volume flow. Only for some very low load points, the volume flow is reduced as the component temperatures are below 65 °C.

The strategy for the operating area of 140 °C target tempera-ture differs. A flow rate compromise must be made in low load operating points. That is because a low flow rate reduces the heat transfer coefficient. The temperature increase of the cool-ant requires a lower inlet temperature at low flow rates, so it



⑩ *Required coolant inlet temperatures (above) and flow rates (below) for motor temperatures at which the best efficiency can be achieved*



⑪ *Average winding temperature in the stator (left) and magnet temperature (right) as a function of the oper-ating points in the torque-speed map with active thermal field weakening.*

does not exceed the 100 °C outlet limit. The lower inlet temperature reduces the components temperatures of the e-motor. A high flow rate leads to a high heat transfer coefficient. Due to the minimal heat up, the inlet temperature can be increased compared to the lower flow rate.

For most operating points, a flow rate of 2 l/min up to 3 l/min is a good compromise between heat transfer and temperature rise. For very low loads, the optimal inlet temperature is above 90 °C. As the loss-es increase with rising torque, the inlet temperature is reduced to maintain the temperature limits of the electric machine.

Between 10,000 rpm with 100 Nm and 16,000 rpm with 50 Nm is a power range with a higher inlet temperature. This tem-perature is increased during the switch from 3 l/min to 10 l/min. This way, the tar-get temperatures can be maintained with a higher heat transfer coefficient and lower coolant heating. A continuous control of the flow rate would eliminate this effect.

The resulting steady-state temperatures for the winding and the magnets are shown in Figure 11. The border between the target temperatures of 60 °C and 140 °C is clearly visible until it disappears at around 10,000 rpm and 100 Nm. For higher loads, the motor losses are so high that the maximum cooling is required – regardless of the target temperature.

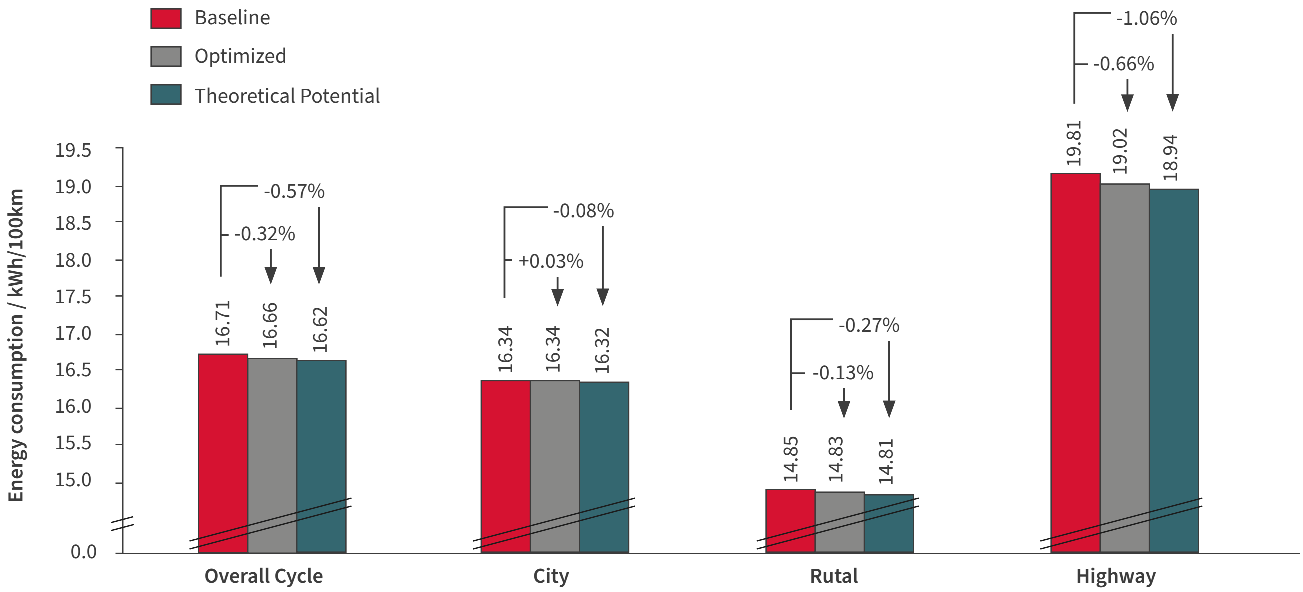
Low-load operation at low speeds with a high target temperature starts at around 100 °C. In this area, little heat is extracted from the electric machine. The coolant is kept near 100 °C as well. For load points above the line from 9000 rpm and 75 Nm to 14,000 rpm and 0 Nm, the control tar-get with temperatures of 140 °C can be achieved.

Use cases in detail: The "Eifel"-cycle and the WLTC

As a first use case, FEV chose a route of 87.6 km as a real-world cycle, which main-ly leads through the Eifel region – a low mountain range in Germany. 20 percent of this driving cycle consists of driving through a city environment, 44 percent of driving through a rural environment and 36 percent of high-way driving. The optimized control strategy with active thermal field weakening, which promotes system heating, achieves energy savings of up to 0.32 percent for the overall cycle compared to the convention-al control strategy (Baseline), as shown in Figure 12. The maximum theoretical potential, which is obtained without taking thermal inertia into account, is 0.57 percent for the overall cycle. Also shown in Figure 12 are the savings that result on the subsections of the driving cycle.

In the official WLTC driving cycle for a class 3 vehicle, as it is required for EU vehicle homologation, electric machines convert most of the energy at rather low torques (compare Figure 9). The WLTP energy consumption is a weighted result of a cold WLTC and a warm WLTC. The results of the simulation for the WLTP are visualized in Figure 13. The energy consumption differentiates between cold and warm WLTP.

For cold starts, the savings in the WLTC with the optimized strategy are rather low. But in preheated conditions – like the warm start WLTC - an overall energy consumption reduction of circa 0.62 percent is achieved. For a 500 km range BEV this results in an overall energy consumption reduction of circa 0.59 percent. Significant benefits are gained in high speed parts of long cycles. They provide a long heat up phase for the motor, contrary to the baseline strategy. This enabled the efficiency increase of about one percentage point over a cold e-motor – when cruising at 120 km/h.



⑫ *Comparison of energy savings using thermal field weakening for compact BEV at the "Eifel"-cycle.*

Active thermal field weakening will offer even greater savings potential for future generations of electric motors. Initial FEV follow-up studies confirm this, because the new machines will have an even higher power density. The increase in power density, in addition to the effects of weight and resource savings, has other advantages for active thermal field weakening. Increased power density, and thus loss density, significantly reduces heating times, which is why high-speed and lightweight concepts will be particularly suitable for thermal field weakening. However, higher loss densities also result in new challenges for innovative cooling concepts. Oil cooling for the rotor can be used in addition to further increase the power density of electric machines and to decouple the rotor temperature from the stator temperature, thus providing a further degree of freedom in temperature control.

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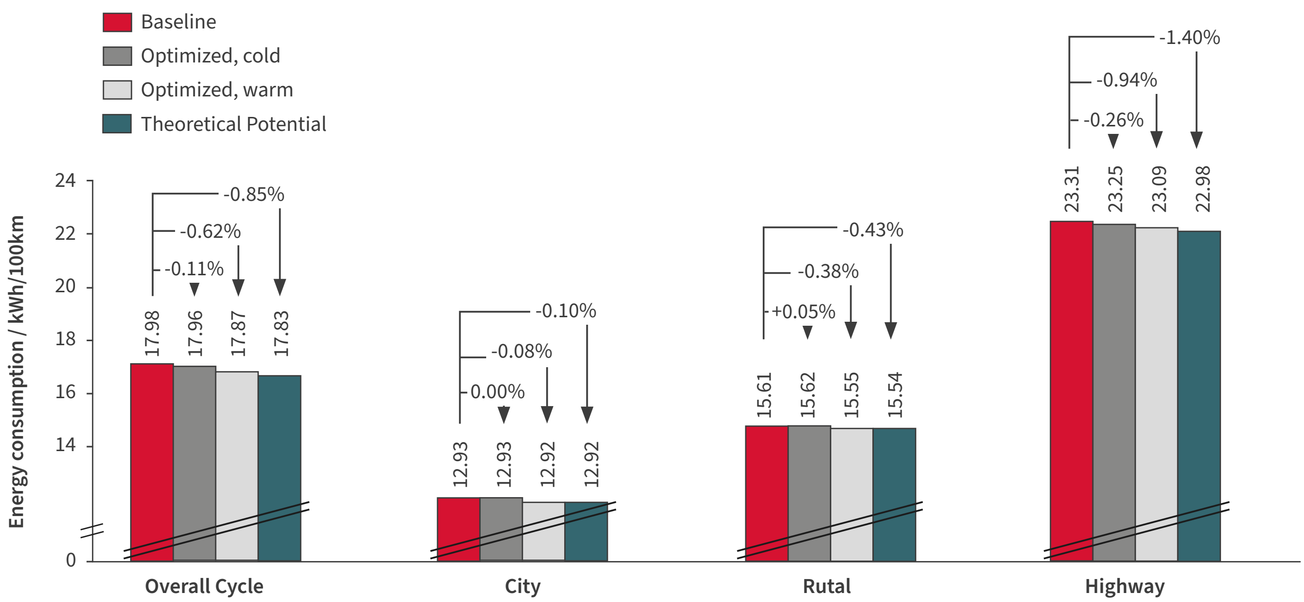


⑬ *Comparison of energy savings using thermal field weakening for compact BEV at the WLTC driving cycle for a class 3 vehicle*

CONFERENCE

ELECTRIFICATION DRIVES SUSTAINABLE MOBILITY, ROADMAP FOR E-FUELS PENDING

A lighter CO_2 backpack of electric cars, the transformational turbo of battery technology, the electrification of heavy-duty transport and hydrogen combustion as a complement: in order to achieve the goals of the Paris Climate Agreement, the participants of FEV's international conference "Zero CO_2 Mobility" in November 2021 in Aachen painted an open technology picture with different approaches to solutions. Host FEV estimates electrification and hydrogen as the most important drivers of sustainable mobility, but at the same time misses a clear roadmap for the increased use of e-fuels.

Most of the technology approaches presented were still dreams of the future, when FEV started the "Zero CO_2 Mobility" six years ago. Dr. Norbert W. Alt, COO of the FEV Group, opened this year's conference, which was once again held in Aachen in compliance with all Corona protection measures, by emphasizing the high speed of the transformation process. The scenarios for the market development of purely battery-electric drives, for example, could not be aggressive enough. The latest FEV forecasts predict that, if the scenario currently under discussion in Brussels is implemented, over 85 percent of new car registrations in Europe will be electrified by 2035.

CO_2 neutrality along the value chain

Vehicle manufacturers are implementing this transformation process at high speed: Volkswagen, for example, used the ID.3 as an example to outline its defossilization program, with which the group aims to achieve virtually climate-neutral individual mobility in passenger cars by 2030. The three key levers: avoiding, reducing and, if necessary, offsetting CO_2 emissions throughout the value chain. Measures include converting production facilities to 100 percent renewable energy sources, using circular economy to recover raw materials for batteries, and investing in the generation of green energy or climate-neutral fuels. Remaining gaps in the carbon footprint are to be closed, for example, by supporting rainforest projects. Calculations already suggest that e-cars in Europe produce only half as much CO_2 emissions over their entire life cycle as comparable vehicles with internal combustion engines. More climate-neutral battery manufacturing processes should help to significantly reduce the so-called CO_2 backpack of e-vehicles.

High energy density, more recycling, better infrastructure

Battery technology is one of the most important accelerators of electrification: according to the experts, more cost-effective, higher-performance solutions will be available much faster than expected. E.g., solid-state batteries: At the FEV conference, a new solid-state battery from Prologium was presented with an energy density of nearly 700 Wh/L, which is double the capacity of batteries currently used in BEVs. Complementing this, experts at the conference shared that a 95 percent battery recycling reuse rate will be possible by 2030.

Zero CO_2 Mobility participants also outlined a number of new approaches in the area of charging infrastructure for e-cars, such as the on-street charging solution from Shell subsidiary Ubitricity. It converts lampposts – some 90 million exist in Europe alone – into charging points by attaching charging stations, using the existing power grid.

① A key driver of mobility transformation discussed at the conference is hydrogen

In heavy-duty transport, alternative drive concepts have also long been in the fast lane. According to commercial vehicle manufacturer Traton, battery-electric trucks will prevail over fuel cell drive systems in the medium and long term in European long-haul transport. This expectation is justified by the higher system and cost efficiency of e-commercial vehicles over the entire life cycle, coupled with higher performance, longer service life and lower energy requirements. Only in the case of a very high variability of the daily range and at the same time large local gaps in the fast-charging infrastructure would the fuel cell truck remain at an advantage. Representatives of the EU project "CoacHyfied" also see great benefits in converting coaches to fuel cell drive systems in order to be able to continue using existing vehicle fleets in a climate-neutral manner while conserving resources.

② At the FEV conference Zero CO_2 Mobility, decision makers of the automotive and energy sectors presented the latest trends and solutions for carbon neutral mobility

Hydrogen on- and non-road

Hydrogen is nevertheless seen as the second driver of the mobility transformation. Among other things, the question of supply was answered in Aachen with reference to the existing European natural gas pipeline network: 23 European gas suppliers have joined forces in the "European Hydrogen Backbone" association, which will be able to convert around 40,000 kilometers of natural gas pipelines for hydrogen transport by 2040. The experts also agreed that the hydrogen combustion engine represents a cost-attractive solution, especially for heavy-duty commercial vehicles, but also offers an option for improved CO_2 balances for non-road applications such as shipping and aviation.

E-fuels: Clear rules for fossil fuel reduction

At the conference, the operation of vehicles with combustion engines with the help of e-fuels formed the third building block in the transformation process to climate-neutral mobility, which is indispensable with regard to existing fleets. In parallel with the coal phase-out roadmap by 2035, however, clear regulations are needed for reducing fossil fuels while at the same time increasing the use of e-fuels, Dr. Alt emphasized in his closing remarks. These would have to include, among other things, the introduction of e-fuel quotas, but also a roadmap for mineral oil suppliers and service station operators up to a complete ban on fossil fuels.

Conclusion

Electromobility is coming much faster than expected, which in turn also means an earlier end than assumed for fossil fuels in internal combustion engines. The industry's commitment to sustainability throughout the value chain is underlined by the increasing switch to renewable energy sources, by circular economy and recycling, especially of batteries. The hydrogen market is in the starting blocks, as is the introduction of fuel cell vehicles in series production. The hydrogen combustion engine is an indispensable complement on the way to achieving the climate targets of the Paris Agreement, as is the use of e-fuels in existing fleets. Both can only be implemented with the help of political support and appropriate targets.

FEV ENERGY

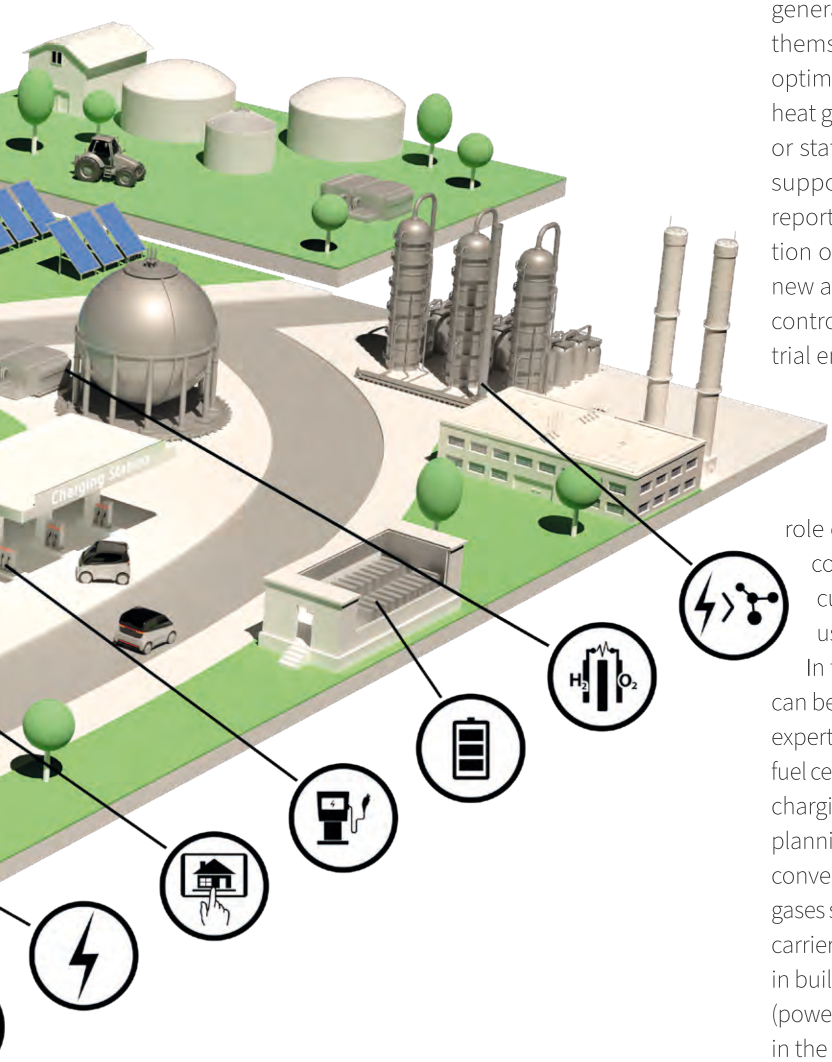
NEW FEV ENERGY BUSINESS AREA OFFERS SOLUTIONS FOR ENERGY SECTOR

As a leading global service provider in vehicle and powertrain development, FEV has strong, historically grown expertise in the use of alternative energies and powertrains in the mobility sector. This expertise will now also benefit the energy sector and industry in their defossilization. To this end, the company has established a new business unit, FEV Energy. From generation to transport and storage to the use of green energy, FEV is able to offer services from a single source for the entire value chain in the future.

No successful energy transition without sector coupling: In order to reduce global CO_2 emissions at the required rapid pace, solutions are needed that intelligently network and holistically optimize the individual sectors – power and heat generation, mobility, and industry. This is the only way to master the challenges of the transformation to a CO_2-neutral society using renewable energy sources such as solar and wind power. Against this background, it is a logical step to transfer the expertise from the mobility sector to the power and heating sector as well. The new FEV Energy business unit ideally complements the existing business areas of the company.

Numerous potential fields of activity

The new business activities are as diverse as the possibilities for generating, storing, transporting and using renewable energies themselves: for example, system design of photovoltaic plants, optimal dimensioning and control of photovoltaic battery storage heat generator systems, fuel cell combined heat and power plants or stationary energy storage systems. FEV Energy also provides support in the preparation of energy audits and sustainability reports. In the automotive sector, the development and integration of bidirectional charging management (BDL) is a promising new area. For this purpose, FEV is developing, for example, smart control strategies for energy management in domestic and industrial environments and for intelligent charging and discharging of connected vehicle batteries.



FEV transfers existing know-how

For all the applications mentioned, FEV Energy assumes the role of a system integrator. Component benchmarking as FEV's core competence is the key to this: although new markets and customers also result in new requirements for the components used, their technical functionality remains largely unchanged. In the first step, FEV Energy is focusing on business models that can be developed quickly with its existing development and testing expertise. These include energy audits, testing and development of fuel cell cogeneration plants and electrolyzers, development of mobile charging and refueling infrastructures, and simulation and project planning of power-to-X applications. These technologies include the conversion and storage of renewable electricity with CO_2 into green gases such as hydrogen or methane (power-to-gas), into liquid energy carriers such as fuels (power-to-liquids) for sustainable mobility and in buildings, or for the synthesis of chemical feedstocks for industry (power-to-chemicals). The target group includes industrial customers in the business-to-business environment.

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