#77 SPECTRUM

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300+ kW fuel cell systems for long-haul truck applications P. 39

Dear Readers,

I am pleased to present the new issue of our customer magazine, "SPECTRUM". For more than four decades, FEV has stood for innovation, leadership, and openness to technology. We continue that tradition in this issue with its diverse topics.

On the following pages, for example, we present the "Dutch WindWheel". An impressive building project that will emit only minimal emissions. FEV Energy is responsible for the planning, development, and implementation of the entire technical building equipment; taking advantage of the FEV Group's extensive expertise in sustainable technology solutions.

Speaking of sustainability, SPECTRUM also talks to the two managing directors of Beyond Materials, a joint venture between FEV Consulting and Mitsubishi Corporation. The company offers specialized strategy and product development consulting for material manufacturers – a field that is becoming increasingly important against the backdrop of circular economy.

In the field of e-mobility, range and charging times are key factors in further increasing market acceptance. Thermal management can have an important influence here. In this context, we present the first results of a model predictive control system that can shorten the charging process and increase the range.

Efficient and reliable high-voltage batteries for e-vehicles also require continuously improved Battery Management Systems. In this SPECTRUM, learn how our engineers developed such a system with cloud connectivity and algorithms based on artificial intelligence as part of the EU Horizon 2020 project "ALBATROSS".

Hydrogen technologies are also an integral part of FEV's activities. In this issue, we present how the power requirements for heavy-duty fuel cell propulsion systems can be analyzed, and how the main components of the system can be dimensioned in terms of efficiency and cost.

I wish you an exciting read – Feel EVolution!

Dr. Patrick Hupperich
President and CEO of the
FEV Group

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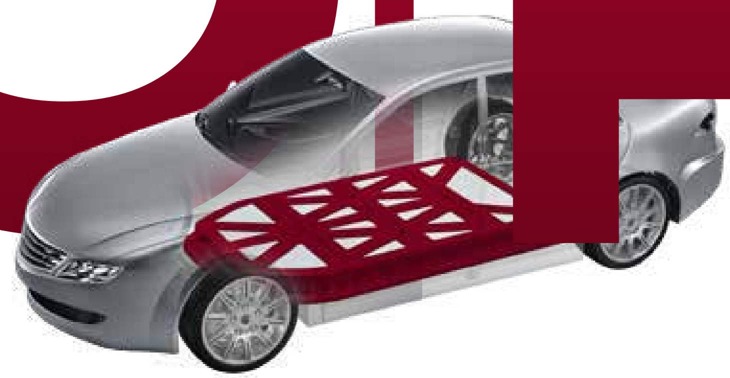


#1
FEV plans energy and building technology for the ***low-emission building*** "The Dutch WindWheel"

Residential and commercial buildings contribute a significant 40 percent to climate-damaging greenhouse gas emissions and thus - along with the transport sector - bear the greatest potential for savings on the way to a zero-emission future. "The Dutch WindWheel" is the prototype of a new generation of sustainable buildings. FEV is the coordinating project partner for this showcase project, in which only minimal emissions are emitted and the necessary energy is generated as much as possible by the plant itself from sustainable sources.

The engineering service provider who has transferred the expertise built up over decades in sustainable mobility solutions to the energy sector is fully responsible for the planning, development and realization of the entire technical building equipment of the property.

This includes the components for power generation from wind and solar energy, as well as energy and battery management, and air conditioning. In addition, FEV is developing a concept for the use of waste water and waste heat to generate energy and for the production of synthetic methanol. In the long term, this will also ensure a sustainable supply of drinking water by means of recycling.

1.
Concept study of "Dutch WindWheel" in Dubai.

»FEV, as the coordinator of the building project, is taking advantage of its many years of expertise in sustainable energy solutions.«

Tourist magnet with sustainable aspirations

The building's eye-catching silhouette combines modern design and various sustainable features. The original intention of the responsible architect Duzan Doepel was to create an extraordinary tourist attraction in the port of Rotterdam (Netherlands). The idea was to show that buildings are capable of making a positive contribution to the climate in the future. The third aspect was to motivate people to reflect on their own energy consumption and to think about potential savings in the building sector. The "Dutch WindWheel" should be able to fulfill a variety of purposes and, depending on wishes and needs, be operated as a commercial or residential building, as a restaurant and hotel, or as a technology hub, as well as in any mixed form. An additional attraction, e.g. for tourists, are the autonomously moving pods on the outside of the building, which allow visitors to enjoy the view over the surrounding countryside.

The interior of the building is defined by generously landscaped green areas that contribute to the improvement of the air and quality of life. As far as possible, local suppliers will be given preference when it comes to the choice of construction material, and sustainable or recycled resources will be used that are in harmony with local conditions. Duzan Doepel emphasizes: "Nature offers us a wide range of possibilities for creating a healthy and sustainable feel-good climate even without high-tech. Our goal is to use these effects first before working with modern systems technology."

Silent power generation

Although wind energy is the name-giver for the building, one looks in vain for conventional wind turbines at the "WindWheel." Instead, the electrical power is generated by electrospraying. This innovative technology uses the Venturi effect created on the building: The shape of the facade creates an air flow that transports positively charged water droplets through a magnetic field of the seven horizontal intermediate levels in the facade, the so-called power beams. This generates electrical voltage. Unlike conventional systems, this technology does not require any moving parts, which significantly reduces noise, vibrations, and shadows.

The second source of energy for the building is the sun. Around 70 percent of the building's facade is equipped with solar panels for this purpose. They also serve as shading elements. Further photovoltaic capacities, including the roofing of the parking areas, are included in the planning of the energy supply. FEV used existing models to carry out and include different load and application cases for this purpose. An intelligent grid and charging management system developed by FEV's engineers uses the vehicle batteries of the parked electric vehicles as additional energy storage and, conversely, uses them as an additional energy source when needed.

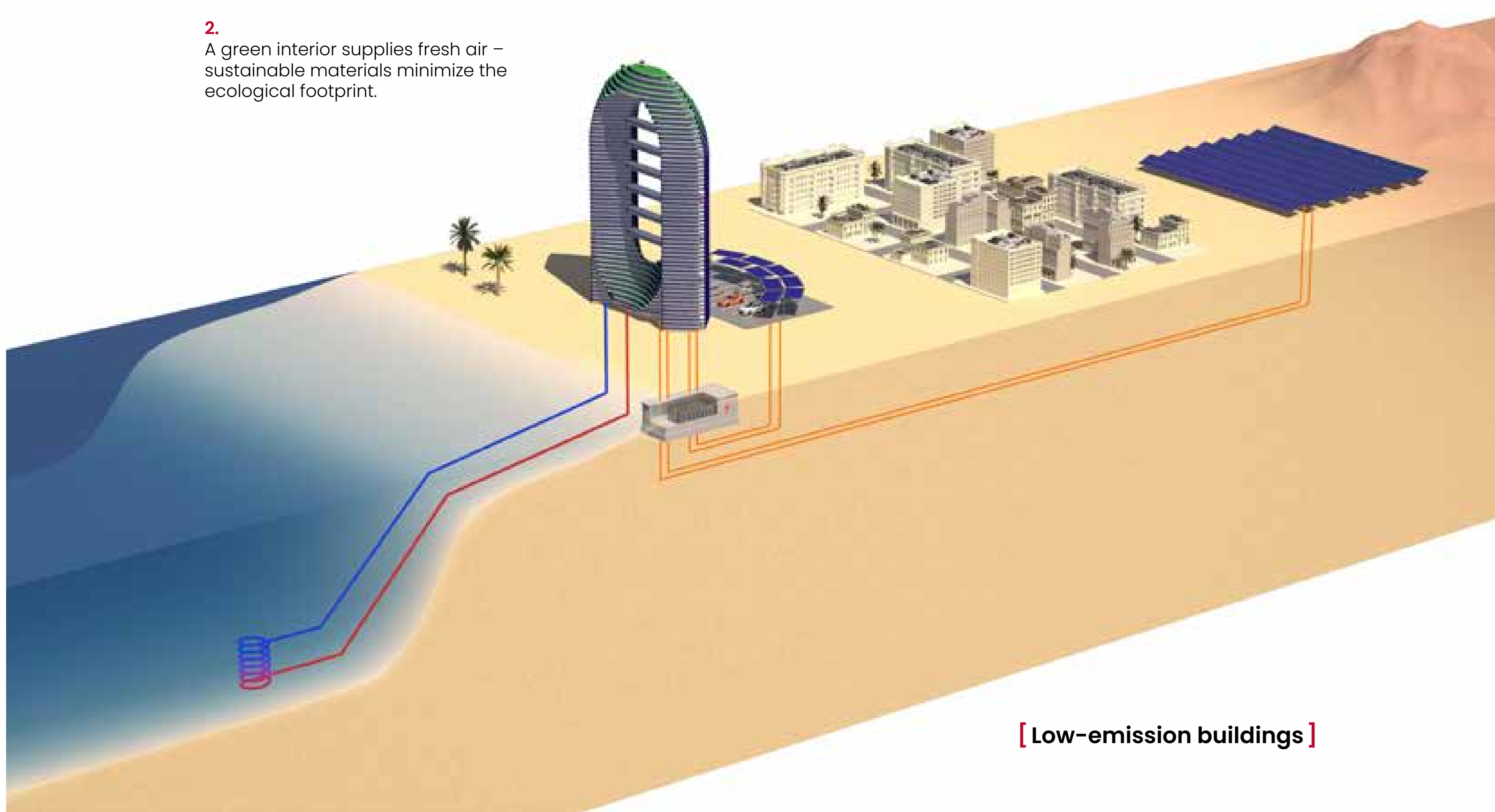
Even with air condition, the planners are focusing on sustainability: The warm exhaust air is fed via generously dimensioned piping into heat exchangers deep below sea level. The cold air is then returned to the building to cool it down.

Patented concept for energy supply

The concept of autarkic and transient operation also includes the treatment of the building's wastewater. FEV brings in a patented concept where wastewater, sludge and organic waste can be treated and used to produce organic methanol. FEV has already proven the feasibility of this technology in several projects and is now bringing this concept to the "Dutch WindWheel" ecosystem. The amounts of potable water generated by this process will be returned to the building's circulation system, supplementing the quantities generated by the processing of rainwater. The use of these advanced technologies is intended to create, in perspective, an environment that can operate with a minimal ecological footprint and, if necessary, recycle the waste and wastewater generated by the apartments and buildings in the neighborhood.

With "The Dutch WindWheel", the architects from Rotterdam are laying the foundation for a new generation of low-emission buildings. FEV is proud to underline its role as a leading global development service provider in this project and to bring its purpose "We drive innovation to help the world evolve" to life in practice.

2.
A green interior supplies fresh air – sustainable materials minimize the ecological footprint.



#2
FEV opens ***state-of-the-art laboratory*** for customized battery systems and cells

FEV is currently expanding its range of services with a new battery cell laboratory at its site in Aachen (Germany). The state-of-the-art facility will focus on analysis and benchmarking of battery cells in terms of performance, lifetime and safety behavior as well as enable cell developments. The lab will start operations in the third quarter of 2023.

As a key component for the performance of battery systems, the cell is crucial for the success of electric vehicles and applications. Therefore, it is of great importance for the development service provider to understand the composition and behavior of the multitude of battery cells in detail.

Due to the offered cell disassembly and analysis services, the creation of prototype cells, safety tests and in-depth material analyses by the laboratory, it is possible to perform a detailed evaluation of the battery cells. For example, the performance, service life, safety behavior, internal structure and material composition are recorded for battery system design, cell design and cell simulation.

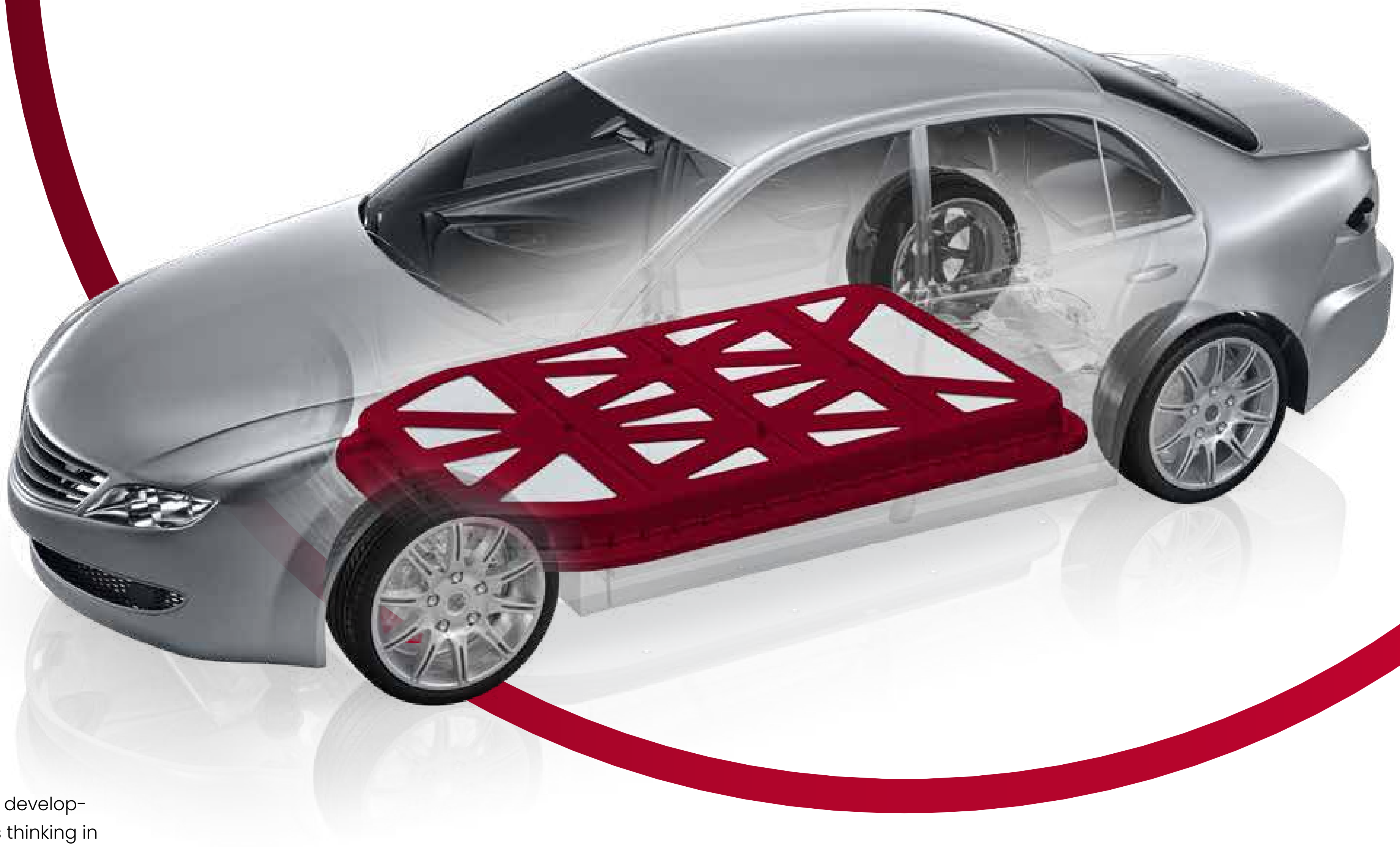
FEV accelerates development of battery systems

This range of competencies and the associated further development of the cell database can significantly accelerate and secure the development process of battery systems. The new laboratory also ideally extends the existing competencies of FEV's battery cell test benches in Germany and France, which are focused on electrical cell characterization. At the same time, FEV's battery cell database provides an always up-to-date and comprehensive overview of for example relevant storage technologies and standard specifications when making decisions.

FEV is a global innovation leader in the field of electromobility including cell development, which is underlined through the inauguration of the new battery cell laboratory in Aachen. Thanks to this range of services, FEV's customers benefit from customized solutions for sustainable mobility as well as shorter development times at lower costs.

The services of the new laboratory at a glance

- In-depth analysis and evaluation of battery cells and their materials for various applications
- Investigation of the safety behavior of the battery cell in case of misuse by means of self-developed high-performance calorimeter (among others usable for especially large battery cells, safety standard tests and complex analyses of the thermal runaway of battery cells)
- Battery cell openings and analysis of the structure and processing of all battery cell components
- Characterization of battery materials in terms of chemical composition, processing and electrochemical behavior (e.g. performance and lifetime)
- Set-up of laboratory cells for the investigation of battery cells and their components for cell and system development
- Characterization and validation of the electrical behavior (performance and lifetime) of the battery cell
- Support of battery system development projects by internal generation of relevant data



#3 *Housing demonstrator* for e-vehicles

FEV together with the production specialist for aluminum hot sheet forming, Impression Technologies (ITL) has presented a battery housing concept for electric vehicles. ITL´s patented HFQ® (Hot Form Quench) aluminum forming technology makes optimum use of the space available for energy storage. For this purpose, the demanding structural requirements for this component are implemented in a novel way. By completely laying the structurally relevant components on the outside and at the same time integrating the battery housing into the overall vehicle, installation space for additional battery cells is created. This leads to a longer range or a reduced installation space requirement while maintaining the same range. The concept developed as part of the joint project of FEV and ITL is to be manufactured and presented as a demonstrator in the coming weeks.

With this latest battery housing development, FEV once again shows its thinking in many directions when it comes to sustainable mobility. The company offers solutions market-demanded – for example, to increase the range of e-mobility. With ITL, the engineering provider has the ideal partner for lightweight construction on board for this project to make the concept tangible for its customers and partners in the form of a demonstrator in a timely manner.

In this new approach, the required structural performance is ensured by an "exoskeleton" concept, which realizes a power flow above and below the battery pack. On the one hand, this keeps the loads occurring in the event of a crash away from the installation space used for the battery cells and at the same time optimizes the rigidity of the overall system (battery and bodyshell).

To achieve the required structural performance in a small installation space, the concept developed by FEV requires the implementation of complex structures with low radii and draft angles. A realization of these structures is possible with ITL's aluminum hot forming technology HFQ®. The HFQ® technology expands FEV's portfolio of available manufacturing technologies for new developments and enables the company to implement more complex structures compared to cold forming technologies. Added to this is the use of high-strength aluminum alloys, which, in conjunction with the HFQ® process, ultimately deliver the required performance in optimized installation space.

With ITL's expertise in ultra-high strength aluminum alloy characterization, design-for-manufacture, forming simulation and production, and FEV's global network in the automotive industry, both companies complement each other perfectly and ensure that all automotive manufacturers can benefit from the novel battery housing concept.

Innovative solutions for the challenges of intelligent mobility

FEV.io

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

#4 FEV software and testing solutions north america celebrates ***20th anniversary***

In the early 2000's, FEV looked to extend the reach of its growing software and testing solutions business into North America — establishing FEV Software and Testing Solutions NA, LLC (STS) in the fall of 2003. Since 2023, the company operates under the new brand FEV test systems. Now, the American team is celebrating the 20th anniversary of its founding with a new facility near FEV North America's main campus in Auburn Hills, Michigan.

"Our previous facility in Redford (Michigan) was simply no longer sufficient to support the business's explosive growth in recent years," commented Allen Arnoldy, Global Vice President, FEV test systems. "Though we continue to accommodate a wide range of more conventional ICE-oriented solutions, the demand for electric and hydrogen-based solutions has been tremendous. This new facility gives us the energy, floor space, lifting capacity, and staff accommodations we need to better meet that demand."

Providing industry-leading software and testing solutions to the commercial marketplace, FEV test systems has long been recognized as the standard for highly specialized test benches and containerized test cells for OEMs and Tier 1 suppliers as they have pushed the limits of conventional powertrain technology. However, these days the business is experiencing significant growth in the areas of electrification, power generation, and even aerospace, which calls for ever more complex and highly dynamic test benches with equally intensive energy demands.

"The mobility landscape is more diverse and competitive now than at arguably any point in its history," continued Arnoldy. "In particular, electrification has brought enormous challenges, with incredibly high voltage and current requirements, inverter speeds, and accelerated timetables for development. Our new location puts the constraints where they belong, working intensely to develop next generation testing solutions, instead of worrying about having the necessary infrastructure to support it."

FEV test systems combines custom-tailored hardware solutions with powerful control, calibration, simulation, and automation products; many of which are the same solutions that FEV Group uses in its own innovative vehicle and propulsion system development. Having integrated the hardware and software solutions in countless configurations, the test systems team is able to generate test beds, benches, and control platforms for virtually any testing or development need imaginable — making it a standout in the FEV Group of businesses and an invaluable partner for mobility manufacturers around the world.

1.
A large bore commercial engine and generator which displays the enormity of solutions frequently designed and constructed by FEV test systems (2010).

»The new facility ensures that we have the prerequisites to meet the enormous demand for electric and hydrogen-based solutions.«

2.
The conventional appearance of the new FEV test systems facility masks the cutting-edge activity occurring within.

3.
The inside of FEV test systems features up-to-date furnishings, abundant natural light, and the latest technical amenities.

#5
Beyond Materials – First choice for the ***material industry***

Beyond Materials Corp. (BM), a joint venture between FEV Consulting GmbH and Mitsubishi Corporation (MC), was founded in Tokyo, Japan in October 2022. The company provides specialized strategy and engineering consulting services to material suppliers and its respective ecosystem. After one year of business, SPECTRUM sat down with the two managing directors Dr. Tetsushi Abe and Johannes Houben.

Johannes Houben
Managing Director
Beyond Materials Corp.

Dr. Tetsushi Abe
Managing Director
Beyond Materials Corp.

Why are you so interested in materials?

Abe: We believe that the role of the materials industry is often underestimated. The demands on future product designs and their underlying materials are becoming increasingly sophisticated and complex. Driven by megatrends such as circular economy, digitalization, electrification, and connected and automated vehicles, innovative and functional materials play a crucial role in modern products. This goes beyond achieving simple design, cost, or weight targets.

Can you give some specific examples?

Houben: Sure. Let us give you three key examples:

Multifunctional materials & requirements
Electrified components require high thermal conductivity and electromagnetic shielding effectiveness. On the other hand, lightweighting requires higher performance in terms of strength, elasticity, or stiffness of materials; while sustainability requires recyclability and a low CO_2 footprint over the life cycle of the materials. The physical limits are often set by materials. We help match demanding applications and diverse requirements with suitable materials.

Recycling
With growing attention on defossilizing the world, more and more companies are working to improve the overall flow of materials by focusing on three "Rs": reducing, reusing and recycling. Each material (metals, polymers, fibers and textiles, etc.) faces different challenges to realize this flow, such as dismantling of end products, sorting of different materials, and the recycling process itself. We help our clients identify appropriate "re"-strategies and can delve into related topics such as recycling processes and how to build a sound business case.

PFAS
PFAS (Per- and Polyfluorinated Alkyl Substances) provide stain-, oil- and water-repellent properties that are very durable, which is why they are known as "forever chemicals". When released, PFAS can harm our environment and our health. Some automotive application examples include gaskets, binder material for cathodes in lithium-ion battery cells, and fuel cell components. We help our customers identify critical PFAS compo-

nents and mitigation strategies in light of a potential decision in favor of a proposal to ban the entire PFAS group by 2025; as well as the resulting implementation timeline of no later than approximately 2038.

How would you describe the challenges of material suppliers?

Abe: Obviously, all material suppliers are different, but you can see a pattern, especially with mid-sized and smaller companies. Material suppliers are undoubtedly the experts in their industry and have a deep understanding of how to make stronger, lighter, or multifunctional materials. However, in the overall supply chain of engineered products, material suppliers are naturally located far from the end user. This requires additional efforts from material suppliers, such as following the latest trends in their end users' needs, demonstrating and validating realistic component designs and material processing conditions, and identifying the right contacts and communication channels to increase awareness of their materials. Rather than just reacting to their direct customers, who are typically the parts suppliers, they need to develop a more proactive approach to providing innovative solutions to unmet needs.

What is your vision for Beyond Materials?

Abe: Our vision is to be the strategic and engineering consulting partner of choice for industrial materials suppliers. We want to enable the materials industry to leverage its unique capabilities beyond its typical value chain position in a global and circular economy.

What separates Beyond Materials from other consulting firms?

Houben: We are the bridge between the mobility industry and the materials industry. Through our deep connection with FEV Group, we have a strong background in many target applications. But at the same time, we speak the language of material suppliers through MC's extensive network and experience in the materials industry. Thanks to this position, we are able to contribute to future development activities of end users (i.e. OEMs and Tier-1s) by promoting technical innovations from the materials industry.

Does this mean that you support only material suppliers as your target customers?

Houben: Our primary focus is on material suppliers, yes. However, we also support component and part manufacturers, or OEMs if they have questions about materials themselves. Basically, we deal with all types of materials, from engineering plastics to adhesives, glass and fiber composites, textiles and nonwovens, ceramics, aluminum, steel and other functional materials, such as those used in battery cells.

How do you support your customers?

Abe: Our customer-centric consulting services can be divided into revenue-up and cost-down services. For the former, we help our customers to increase their revenue potential by identifying new markets for the existing product portfolio, as well as new product opportunities based on their individual capabilities (through Market & Technology Intelligence, Strategy Development, Product Development, Marketing Support and more).
On the other hand, our cost-down services are aimed at ensuring the long-term profitability of our customers. We support this with services such as Portfolio Management, Organizational Excellence, Strategic Costing and Sourcing.

1.
Beyond Materials service offerings and relevant hot topics.

Can you please give us some examples?

Abe: It can be difficult for material suppliers to identify long-term trends in their target markets, as their day-to-day business is often driven by short-term customer demands. This is where our Market & Technology Intelligence service can provide valuable insights for strategic decision making. We leverage FEV's deep understanding of various application technologies, coupled with MC's broad network of materials companies to develop a continuously updated applications-materials database. The database is a comprehensive collection of automotive industry pain points and potential material-based solutions. This serves as an excellent foundation for identifying new product opportunities and is typically followed by a sound go-to-market strategy.

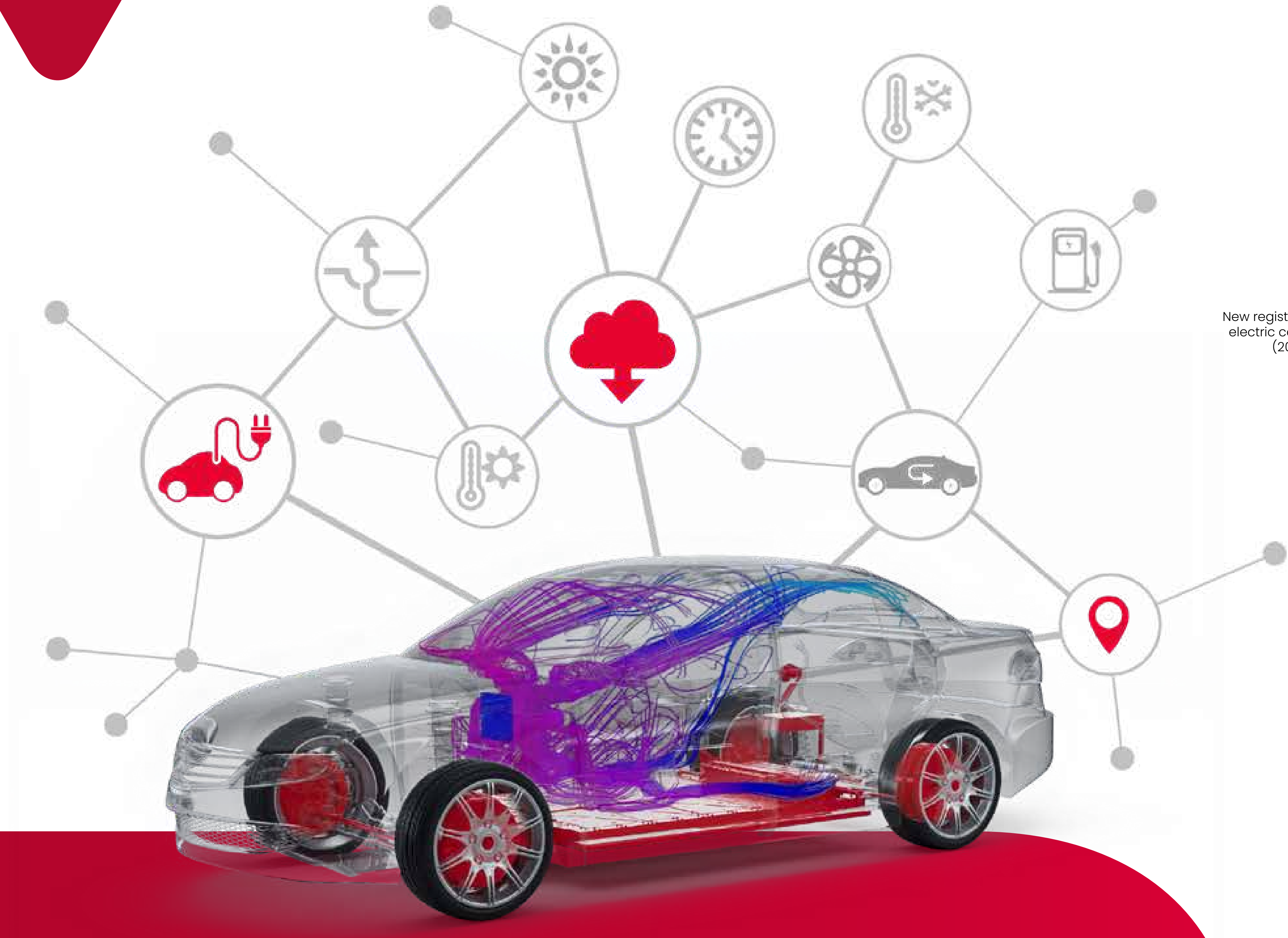
Houben: And actually, we can and frequently do go well beyond that. We support our customers in the successful implementation of new product opportunities by assisting with our product development service. Helping to develop superior material specifications based on current automotive pain points is just the first step. When approaching new customers, we believe it is important to demonstrate that the materials offered will improve the customer's target performance. Whether it is weight reduction, energy efficiency or durability, customers often expect proof. Together with our materials and engineering experts, we help our customers develop and validate hardware demonstrators. This helps material suppliers demonstrate the superiority of their material, while ensuring customer confidence in their brand and product.

So, what is the plan for your second year of Beyond Materials?

Houben: We are just getting started. As a new company, we want to continue to strengthen our service offerings and further tailor them to the needs of our customers. But we also want to expand into non-conventional consulting services by identifying new functions and scalable digital solutions that will help the material suppliers and customers to connect. There is much more to come!

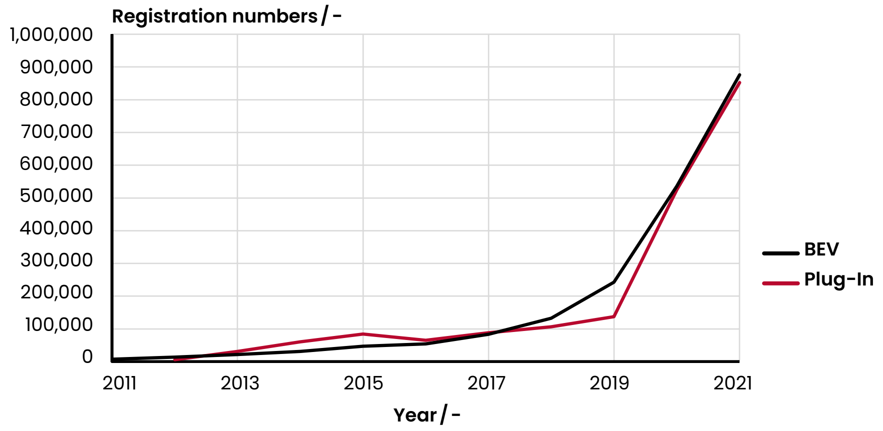
Thank you for your time!

beyond-materials.jp



#6
Model predictive thermal management control strategies for ***battery electric vehicles***

Electromobility in Europe is on a strong growth path. This becomes particularly clear when you take a look at the registration numbers in Europe (Figure 1). While only 7,179 battery electric vehicles (BEV) and Plug-In electric vehicles were registered in 2011, the statistics have risen rapidly since then with 1,728,967 vehicles in this category being registered in 2021.

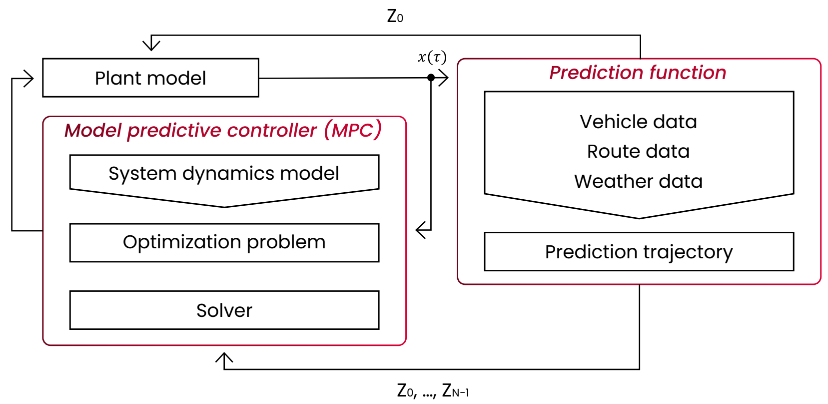


1. New registrations of electric cars, EU-27 (2011 - 2021).

In order to enhance customer acceptance, there is a need for further improvement in both range and charging times, as these elements significantly influence the purchasing decision. Electric vehicle thermal management can help improve these criteria. This article presents the general principles and first results of the model-predictive controller (MPC) for BEV.

Design of the MPC

The developed model-in-the-loop (MIL) environment is illustrated in Figure 2. It consists of the plant model, the prediction function, and the model-predictive controller. The plant model is the virtual representation of the vehicle. It was validated using measurement data under different environmental conditions. The outputs of the plant models are the integrated system states x(τ). These are passed on to both the prediction function and the MPC for further processing.



2. Schematic structure of the MIL simulation environment.

In the prediction function, the external conditions, such as the weather and route information, are determined for the trip (z_0) and their trajectories are calculated in advance. These describe the respective parameters as a prediction from the current point in time to the end of the prediction horizon N_p.

The MPC receives the calculated states from the plant model and the predicted parameters from the prediction function. It contains the system dynamic model, the formulated optimization problem, and the solution. The optimization problem and solution are provided by the acados framework. In order to guarantee real-time capability, it is important to ensure that the overall computing time of the models is as short as possible. At the same time, however, the system and its inertias and characteristic properties must be represented precisely. In the following, the models for battery cooling and cabin conditioning will be explained. The MPC predicts the control trajectory until the prediction horizon N_p is reached.

Battery model

The battery model can be divided into two sub-models – an electrical sub-model, and a thermal one. All electrical states and parameters, such as capacitances, voltages and resistances, are calculated in the electrical sub model. The thermal sub-model includes the temperatures that occur due to the heat flows between different subsystems of the battery with the corresponding heat transfer coefficients.

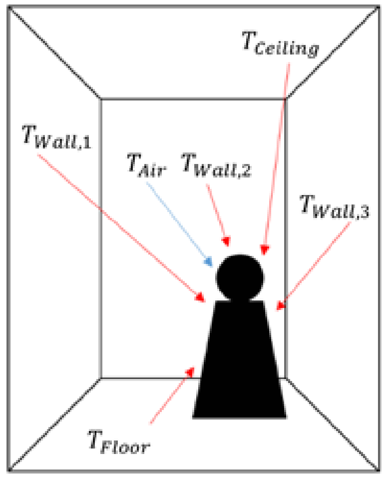
The battery was modelled with the parameters of a PHEV2 traction battery with a cell arrangement of 96S0P and a maximum capacity of 50 Ah. The cells are grouped into eight stacks which all have the same electrical and thermal characteristics.

The electrical model calculates the system variables as a function of the battery current I and passes on the voltages U relevant for heat generation $\dot{Q}$ in the battery to the thermal model. Within the thermal model, the heat input due to ohmic losses is then determined. The battery parameters are also dependent on the stack temperatures T_{Stack}, which is why these are also included in the electrical model. The thermal model calculates the relevant stack temperature as a function of the thermal system coupled to the battery and the ambient temperature.

For a numerically efficient modelling of the battery temperatures, a thermal network with concentrated parameters was developed. The individual physical components of the battery body are assigned as thermal masses, which are connected to the surrounding thermal masses via thermal resistances. A total of 22 thermal masses are modelled for the battery.

The thermal system model is limited to the system components relevant for battery temperature control.

3.
Principle of equivalent temperature – schematic illustration.



Cabin model

The cabin model was designed to investigate the optimization of the energy demand for cabin conditioning. For this purpose, a one zone model of a vehicle cabin was created, and the thermal masses and HVAC (Heating Ventilation Air Condition) contained therein, were modelled. The air flow can be taken directly from both the environment (fresh air mode) and the cabin (recirculation mode). It is possible to vary the recirculation rate continuously between "0" and "1". The impact the occupants have on the heating and air quality of the vehicle was considered. As a result, the CO_2 concentration in the cabin increases when the recirculation rate is increased.

Heating surfaces can contribute to a reduction of the energy demand for the vehicle cabin. Consideration of the heat radiation of the surfaces is essential to evaluate the potential of this technology. One way to do this is to determine the equivalent temperature. This representative temperature should reflect the perception of the indoor climate. The concept of equivalent temperature is shown in Figure 3. In the illustration, an individual is in a room with a constant air temperature T_{Air}. The temperature perception of the test person now depends not only on the air temperature, but also on the temperature of the surrounding walls $T_{Wall,i}$, the floor T_{Floor}, and the ceiling $T_{Ceiling}$. If the surrounding surfaces are actively heated, the person's perception of temperature inside the room can be changed. Of course, many other factors are relevant as well. In addition, the heating surfaces must also be added to the model. A separate thermal mass is defined for the heating surface for this purpose.

Investigation of predictive control strategies

The MPC will be demonstrated in two different applications. The first case deals with the conditioning of the vehicle battery. Subsequently, the influence of the heating surfaces and their integration into the overall strategy will be explained.

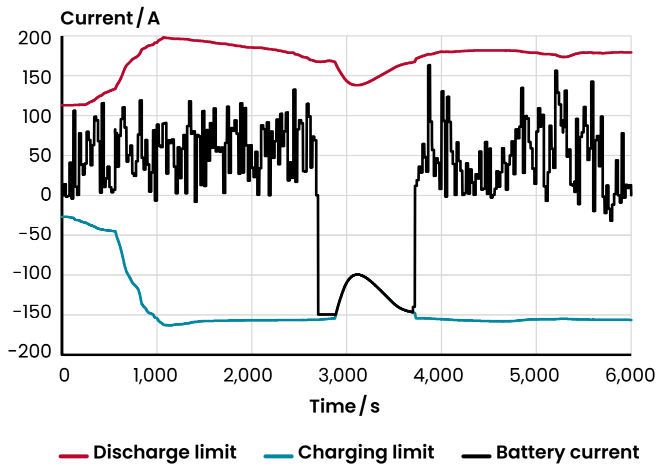
Predictive battery conditioning

The scenario for the investigation of battery conditioning is based on a driving profile that was recorded in real traffic. The speed profile contains city traffic, country roads and the motorway. A total of 134 km was covered. An ambient temperature of -15 °C was assumed for the simulation. The starting temperature of the stacks was set to -3 °C. The vehicle always starts with a state of charge (SoC) of 90 percent. A charging stop is necessary as soon as a SoC of 15 percent is reached. It is not considered whether a charging station is available at this position on the route. The maximum charging speed is limited to a rate of 3C. Additional restrictions are only imposed by the temperature and SoC-dependent charging and discharging limits of the battery.

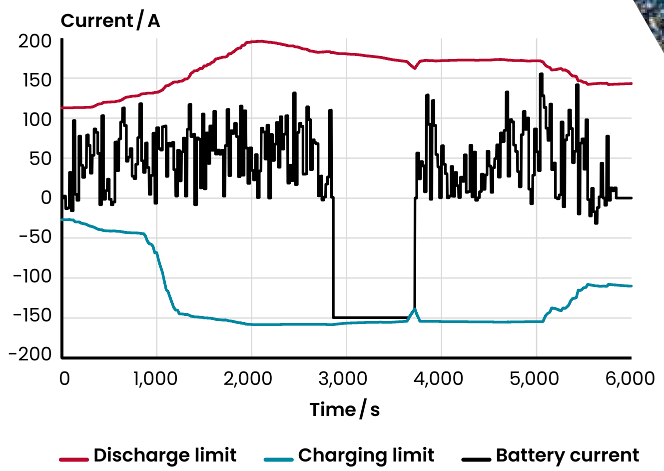
The baseline is the rule-based control from the test vehicle. The battery is actively heated below a stack temperature of 10 °C. Cooling starts as soon as the stack temperature exceeds 40 °C. In Figure 4, the current profile of this simulation can be found in the black line. The red line represents the discharge limit of the battery and the blue line represents the charging limit of the battery. With the rule-based approach a charging stop was necessary after approximately 68 km (~ 2,700 s). The maximum charging speed could not be used for the full duration of the charging event. Therefore, the charging time results to ~16 min.

In comparison, an MPC-based thermal strategy was investigated. Its goal is to condition the battery in such a way that the predicted battery power can be provided during driving and charging. Figure 5 displays the current profile of the battery using the MPC control strategy.

It becomes evident that the maximum charging rate of 3C can be maintained using the MPC. The total time at the charging equals ~15 min (10.2 percent reduction). The charging stop is later than before. The vehicle needs to be charged after 70 km (~2,850 s). This equals an improvement in the driving range of 2.94 percent. The main benefits are achieved by a reduced active heating of the battery and the avoidance of overcooling.



4.
Current profile of the battery using the rule-based control strategy.

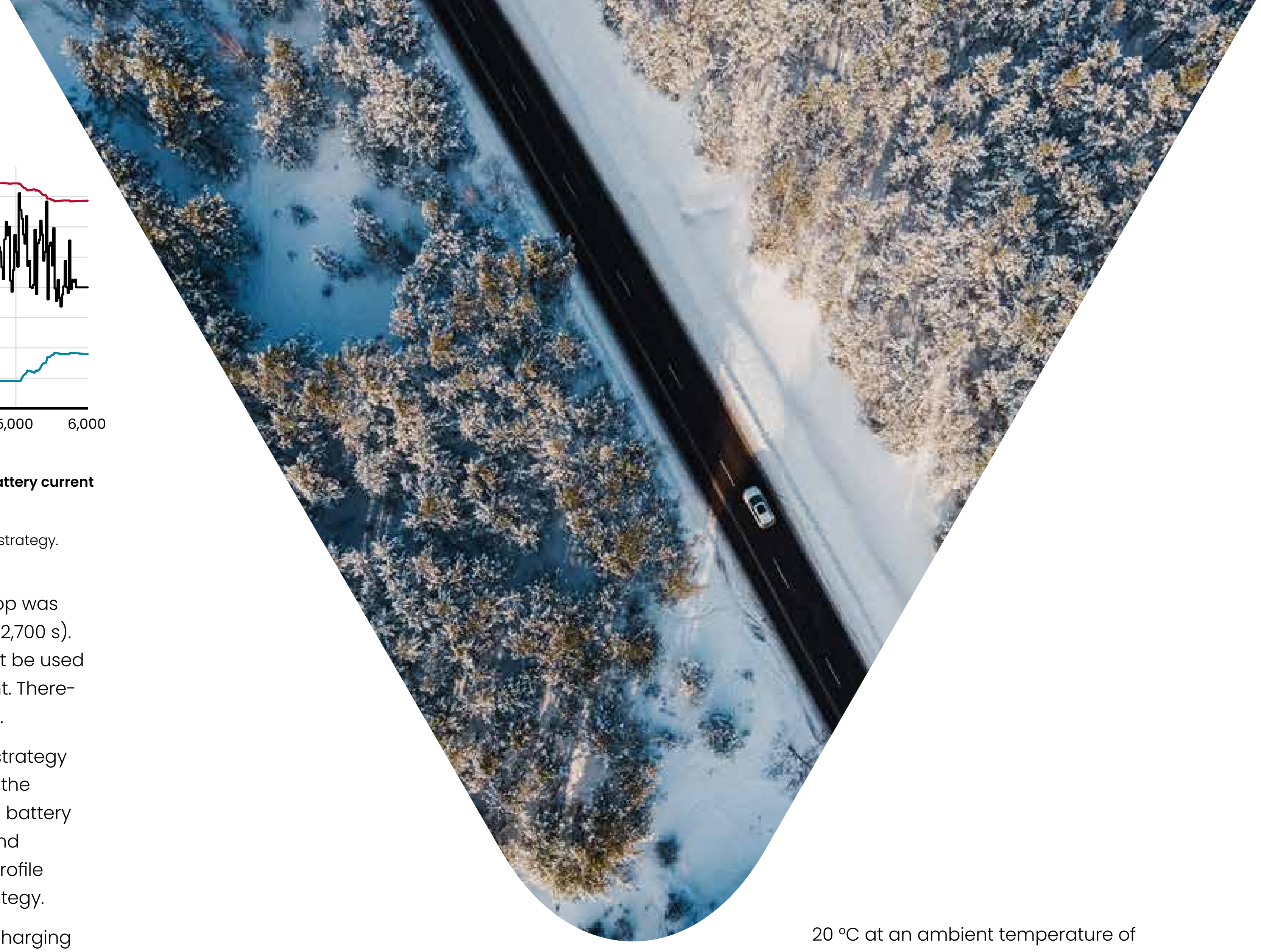


5.
Current profile of the battery using the MPC control strategy.

Predicted cabin conditioning – surface heating

In this section, the MPC control approach is investigated for cabin conditioning. In an MPC was used which was capable of controlling the air mass flow entering the cabin, the recirculation rate, and the necessary heating power, which was provided by a high voltage air heater. The target temperature for the cabin was set to 20 °C at an ambient temperature of -10 °C. Also, solar radiation of 200 W/m² was assumed for a test drive in a WLTC class 3. The MPC aimed to reach the selected temperature set point for the interior while minimizing the electrical power consumption. As an additional constraint the MPC was forced to maintain certain thresholds for the CO_2 concentration. Three different limits were chosen: 5,000 ppm, 2,500 ppm, and 1,200 ppm. The MPC was compared to a simple rule-based approach. The recirculation rate was kept constant during the operation. In Figure 6 the results of former investigations are summarized.

The effect of heated panels on the energy consumption for cabin conditioning is investigated in this paper for the same scenario with the activated surface heating (SH). Therefore, the set point for the cabin temperature remains at 20 °C for the equivalent temperature. In Figure 9 the comparison between the MPC approach without SH and with SH is illustrated for the three different CO_2 limitations.

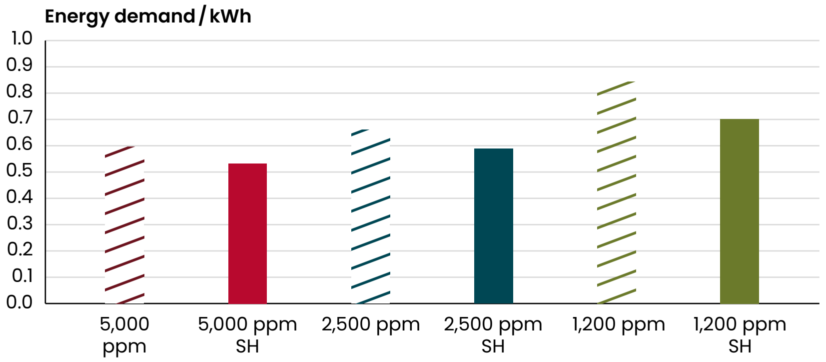


Control approach	Energy demand / kWh	Relative savings / %
RB / 50 % recirculation	1.05	/
MPC / 5,000 ppm	0.60	-43,4 %
MPC / 2,500 ppm	0.66	-37,3 %
MPC / 1,200 ppm	0.84	-19,2 %

6.
Comparison of the energy demand for cabin conditioning.

»With strict CO_2 limitations, an energy saving potential of up to 16.7 percent was identified.«

The shaded bars in the diagram represent the results of the MPC approach without the heating surfaces. For all three CO_2 limits, additional energy can be saved by using the heating surfaces. The savings potential even increases with stricter CO_2 concentration requirements. This is due to the fact that more fresh air has to be used to maintain the air quality within the cabin. Whereas at 5,000 ppm and 2,500 ppm, about 11 percent of the energy can be saved, the relative savings go up to 16.7 percent for the recommended value of 1,200 ppm.



7. Comparison of the Energy Demand for the MPC Approach for cabin conditioning with and without Surface Heating (SH).

Conclusion and summary

In this article, the application of an MPC control strategy for BEV thermal management was investigated. For battery conditioning, a trip at -15 °C was simulated. The results show that the charging event could be shortened by up to 10.2 percent by using an MPC. At the same time, an effective range increase of 2.94 percent was achieved.

For cabin conditioning, the use of heated panels to decrease the energy demand for the cabin condition was evaluated. The simulations with the heated panels show that additional energy can be saved. Especially for strict limitations for the CO_2 concentration an energy saving potential of up to 16.7 percent was identified for the implementation of surface heating with an MPC approach.

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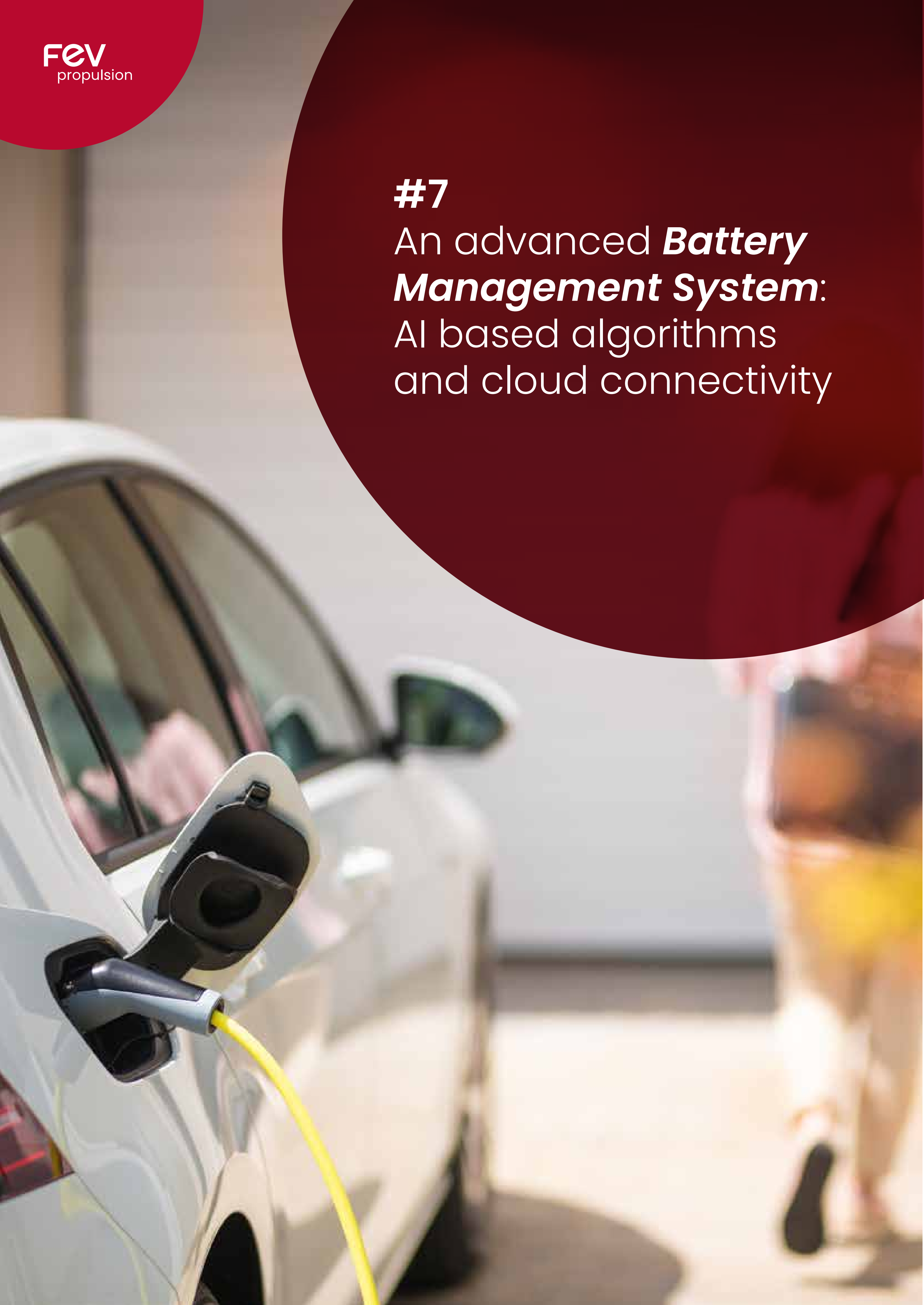


#7
An advanced ***Battery Management System***: AI based algorithms and cloud connectivity

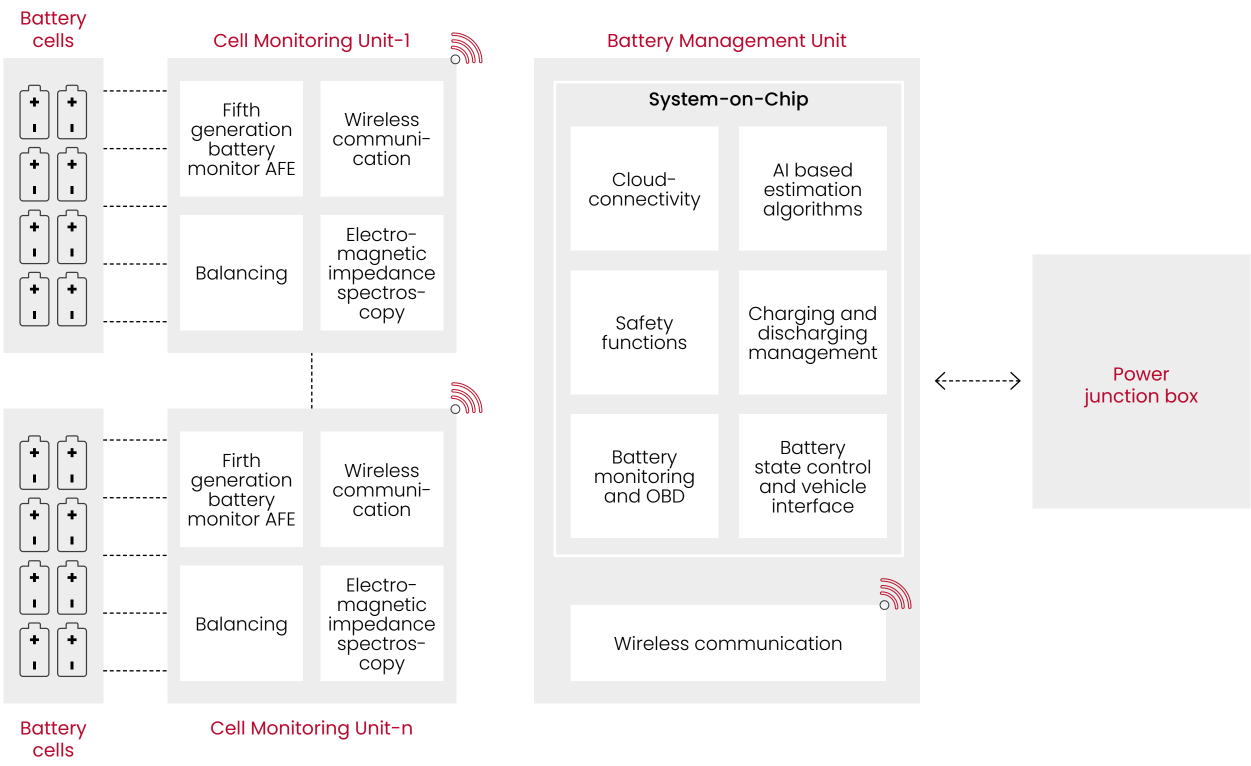
The increasing demand for improved electric vehicles around the world requires more efficient and reliable high voltage batteries for the automotive industry, and this can only be realized with advanced battery management systems (BMS). Since 2006, FEV has been developing both hardware and software for BMSs, offering a broad service portfolio from development of advanced software functions to turn-key, ready-to-use BMS solutions. Most recently, a cloud connected BMS with AI-based algorithms has been developed by FEV engineers within the scope of the European Union-funded Horizon 2020 project, named ALBATROSS.

The Battery Management System is a key component of battery packs, responsible for monitoring and controlling the performance of batteries, ensuring optimum charging and discharging, and maximizing the overall life of the battery packs. In addition, Battery Management Systems play a critical role in ensuring the safety of the battery pack by monitoring temperature, voltage and current.

FEV offers BMS solutions with features beyond state-of-the-art technology

The Master-Slave topology architecture, which consists of a Battery Management Unit (BMU) and numerous Cell Monitoring Units (CMU), is a fundamental design of FEV within the ALBATROSS project. The BMU collects data from individual cells inside the battery pack via the Cell Monitoring Units (CMUs). Working in conjunction with the CMUs, the BMU provides a comprehensive view of battery performance, enabling precise control and optimization of the charge and discharge processes.

»FEV offers a broad BMS service portfolio up to turnkey system solutions.«



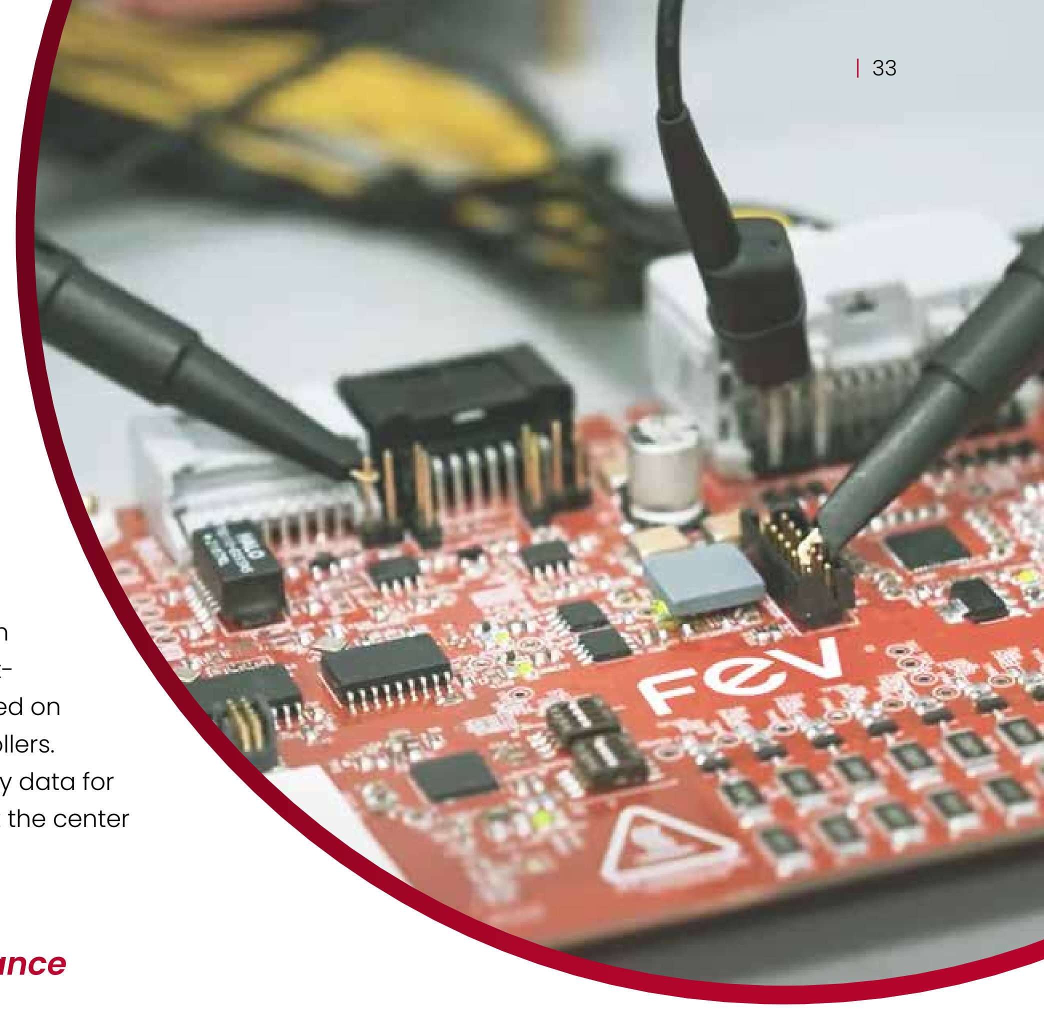
Fifth-generation cell monitoring AFE

The ALBATROSS Battery Management System has been developed using the latest technologies to improve performance and safety. Battery Management Systems have various high-level algorithms that run on the BMU. However, all algorithms are built around the most basic and important function of the CMU, which is voltage measurement. BMS algorithms cannot properly function without an accurate and reliable voltage measurement. The Albatross BMS is designed with fifth-generation, cutting-edge battery stack monitoring featuring Analog Front End (AFE) chips, which serve to optimize the overall performance. These advanced AFE chips offer several features that improve the functionality and efficiency of the system. A key feature is the ability to accurately monitor the voltage of each battery cell, allowing precise control of the charge and discharge process. In addition, the fifth-generation ASIC chips enable precise temperature monitoring, ensuring that the battery operates within safe temperature limits. Furthermore, AFE used in CMUs provides a "functional-safety ready" design-base which in turn can be developed up to ASIL-D rating.

Wireless Battery Management Systems

Wireless Battery Management Systems are a revolutionary advancement in battery monitoring and control, setting new standards for efficiency and convenience. These state-of-the-art systems use wireless communication protocols to transmit vital battery data in real time, unlike traditional wired systems. This eliminates the need for cumbersome cables, making installation easier while increasing flexibility, which is simply a game changer for various applications. In addition, wireless Battery Management Systems are highly scalable, able to be easily adapted to different battery pack configurations. This adaptability allows manufacturers to optimize space utilization.

Another notable feature of wireless Battery Management Systems is their ability to eliminate the need for communication network cables to be routed around the battery pack. This approach results in a cleaner and more efficient system design by streamlining the integration of battery management units and cell monitoring units.



The latest wireless microcontrollers are used to develop the FEV CMUs. Each CMU has its own wireless microcontroller, as does the BMU, in addition to an advanced system-on-chip. A network with a star topology is formed on top of these wireless microcontrollers. The BMU, which collects all battery data for use in advanced algorithms, is at the center of this network.

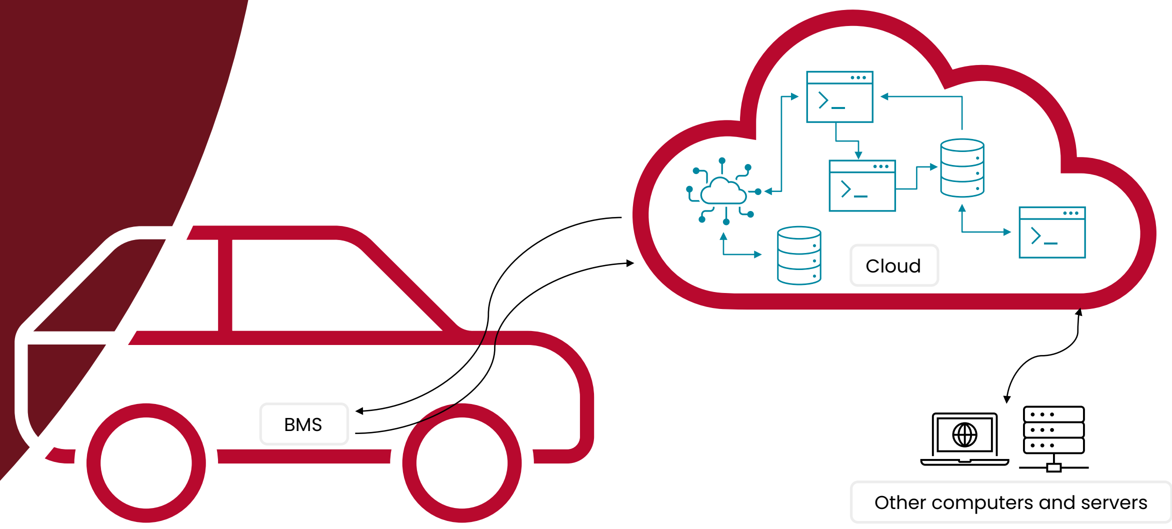
Electrochemical impedance spectroscopy

Electrochemical impedance spectroscopy (EIS) is a powerful technique that is used to analyze the electrochemical properties of batteries and other electrochemical systems. It involves applying a small amplitude alternating current (AC) signal to a battery or electrochemical cell and measuring the resulting current response. This is done over a range of frequencies.

Another cutting-edge technology used in this project is the on-board Electrochemical Impedance Spectroscopy (EIS) analysis technique. To apply EIS on board, specialized hardware is integrated into the Battery Management System. This hardware generates and applies a small AC signal to the battery cells. The response of the battery cells is measured at different frequencies. A Battery Management System with on-board EIS capability allows the BMS algorithms to be enhanced. In addition, thermal propagation and fault detection algorithms can benefit from EIS data to improve overall battery safety. In summary, on-board EIS measurements along with advanced algorithms provide valuable insights into battery performance, health and thermal behavior.

The system on chip

The System on Chip (SoC) stands out as a pioneering solution that brings forth a multitude of advantages through its dedicated cores for various operations and by implementing highly effective Inter-Processor Communication (IPC) mechanisms. The architecture's dedicated cores are specialized for signal and image processing, floating point vector calculation, and real-time control. Thus, the ability to assign specific tasks to dedicated cores not only ensures the optimal utilization of computational resources but also paves the way for unparalleled performance in their respective domains. In ALBATROSS, FEV takes advantage of this sophisticated nature of the SoC to improve the precision and efficiency of highly complex Ai based algorithms and control mechanisms. Moreover, FEV aims to create a new architecture that allows battery systems to manage more complex solutions as part of software-defined future.



The telematic system solution: Information exchange between BMS and cloud

The telematics system solutions which allow the information exchange between a vehicle and the central authority have become of greater importance as the global demand for e-mobility solutions increases. A typical telematics system is composed of one or more mobile vehicle systems and a stationary remote system. The vehicle systems communicate with the remote system utilizing radio, cellular or satellite communication for transmitting vehicle-specific data, like the vehicle positions or data from sensors or electronic control units and receiving control messages or over-the-air firmware and security patches. The remote system usually includes a database for storing the vehicle-specific data or messages.

The system design starts with a definition of the system features and data to be made available on the remote cloud system. The features of the cloud system can be backing up vehicle-specific data for fleet management and analytics, running online Battery Management System algorithms or distributing algorithm improvements to the vehicles. The vehicle-specific data might include voltage, current and temperature measurements of a battery pack, higher level battery management calculations e.g., state of charge (SoC), state of power (SoP) and state of health (SoH), and battery model parameters. The vehicle-cloud communication requirements and cloud database & storage requirements are defined by the intended features and data specifications.

The cloud systems embody data receiver and data transmitter services for receiving measurements and calculations from the vehicles, transmitting BMS algorithm outputs to the related vehicles, and distributing firmware patches or packages to the fleet while MQTT and HTTP are mostly used communication protocols. As a part of information security, authentication methods of using client certificates and applying custom authentication schemes based on single or multiple factors, and secure communication protocols like TLS, are employable. The data from the received messages are generally stored in relational or nonrelational databases where encryption might also be applied for protecting the data. For running online BMS algorithms, one or more computing services with related computing resources needs to be incorporated, configured based on memory, storage and performance requirements of the algorithm, and granted with required permissions for accessing databases or other computing services. Pipelines are also used to automate the machine learning lifecycle processes of training, evaluating, registering and deploying models for BMS estimations.

Distributing firmware packages or algorithm improvement patches to the vehicles from the remote system are enabled by incorporating firmware over-the-air (FOTA) feature into the cloud system. Packages or patches to be distributed can be prepared on the cloud system or be uploaded to the cloud system as part of the related pipelines while frontend and backend computing services are responsible for providing upload ability with authorization and access controls and governing distribution of the packages to the related vehicles.

Conventional BMS solutions utilize embedded hardware and have limited compute power; cloud connected BMS solutions however overcome this challenge leveraging the scalability, elasticity and flexibility that are offered by cloud systems. As a result of the increasing global demand for e-mobility solutions, battery management has been and will likely continue being a key area of application for telematics system solutions.

The application software: artificial intelligence based advanced algorithms

Application software is the key area to be developed in the scope of ALBATROSS project. FEV teams targets beyond state-of-the-art precision and accuracy through harnessing the power of AI technology in the calculation of critical battery parameters such as, State of Charge (SoC) and State of Health (SoH). One of the innovative features of APSW, developed within the scope of ALBATROSS, is Anode Controlled Charging (ACC). It takes a role in fast charging applications by adjusting charge current and maximizes charging speed without effecting cell aging performance. The novel methodologies used by FEV's engineers, both in the development of SoC estimation and, o ACC function have been patented:

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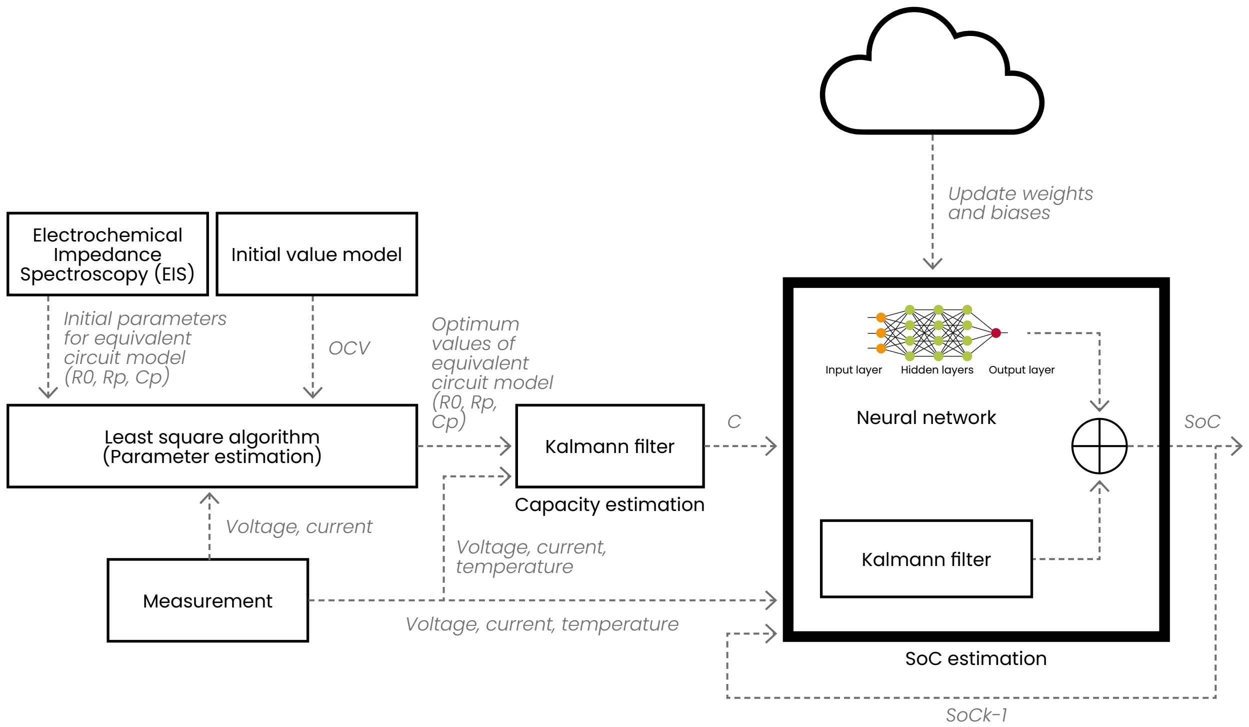
State of Charge (SoC)
It presents an innovative method for SoC estimation by using both neural network and Kalman Filter.

State of Health (SoH)
It offers an algorithm with high accuracy by saving collected data in the cloud service and by using machine learning.

Anode Control Charging (ACC)
It presents an innovative method for anode controlled charging by optimizing charging by using neural network, cloud operations and electrochemical cell modelling methods.



#8 **300+ kW fuel cell systems** for long-haul truck applications

What improvements can be expected with this next generation of fuel cell systems?

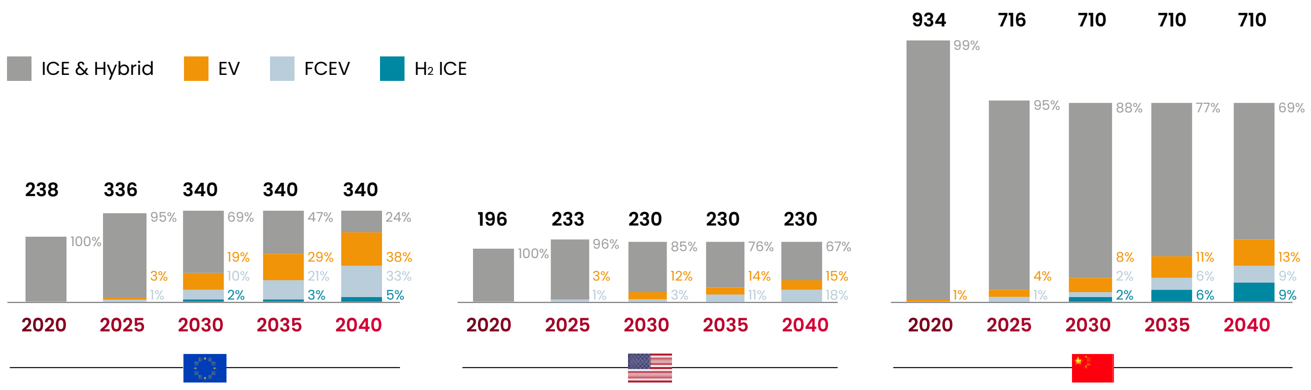
According to a recent ICCT study, trucks are responsible for approximately 22% of carbon dioxide emissions from on-road traffic in the European Union.

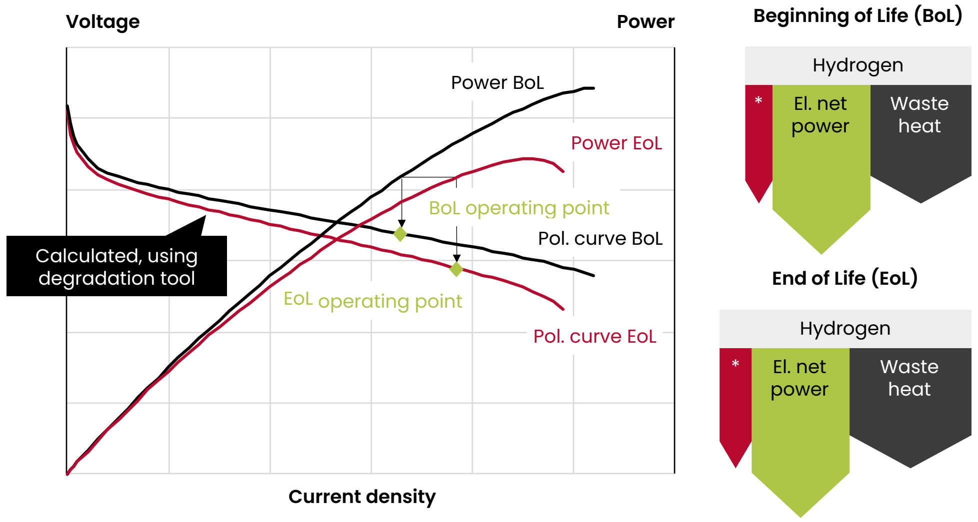
By 2030, the CO_2 emissions of heavy trucks must be reduced by 30% relatively to the 2019/2020 baseline. By 2040, all major truck OEMs have announced plans to sell vehicles with 100% fossil-free propulsion systems. Fuel cell electric powertrains are a cornerstone of this transition.

The European Union, the USA and China are the largest single markets for heavy-duty trucks. In 2040, FEV projects sales volumes for heavy-duty vehicles to be approximately 340,000 in the EU, 230,000 in the USA and 710,000 in China (Figure 1). Among these vehicles 33% are expected to be fuel cell electric in the EU. In the USA and China, the shares are somewhat lower with 18% and 9%, respectively; corresponding to annual sales of approximately 220,000 fuel cell (FC) heavy-duty trucks by 2040.

In the European Union, most of the heavy-duty trucks are equipped with 300 to 370 kW Diesel engines. The usual power in the USA is somewhat higher and ranges between 320 and 400 kW due to the higher speed and payload. The strategy of many truck OEMs and Tier 1 suppliers of fuel cell systems is to adopt a modularization strategy to get into volumes at fuel cell stack and system level as fast as possible. Stacks and systems of 80 to 150 kW each can be combined to provide appropriate power output for various applications and markets.

1.
FEV propulsion system sales forecast for heavy-duty commercial vehicles in EU, USA and China, sales volume in thousand vehicles *(ICE: Internal Combustion Engine, EV: Electric Vehicle, FCEV: Fuel Cell Electric Vehicle, H_2 ICE: Hydrogen Internal Combustion Engine)*





3.
Generalized relation between fuel cell net power output and waste heat, as well as parasitic losses by the auxiliaries BoP (balance of plant) components.

** Auxiliaries*

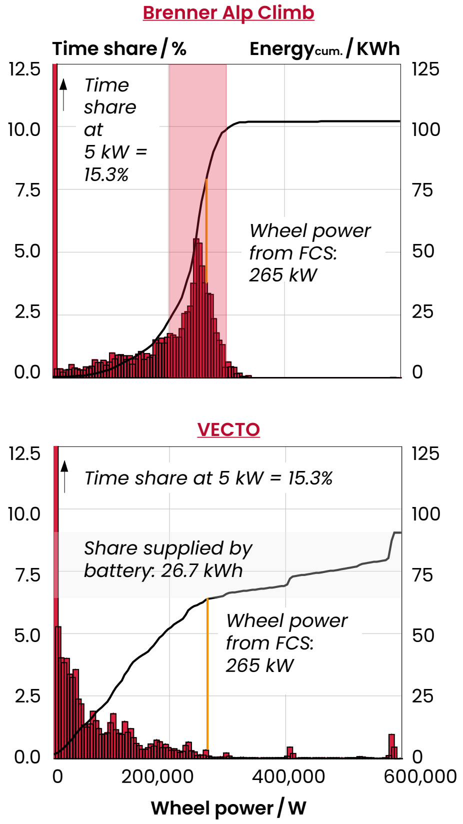
Propulsion system requirements and system sizing for heavy duty trucks

To derive the power requirements of a typical European HD propulsion system, a longitudinal simulation model is used and two drive cycles, namely the "Brenner Alp Climb" and the "VECTO long-haul cycle", are used. The resulting wheel power distribution is shown in Figure 2 together with the cumulated energy demand of the cycle.

The graph shows that the cumulated energy curve of the "Brenner Alp Climb" is sharply rising between 200 and 300 kW due to the high energy demand during the climb. Assuming that the vehicle is equipped with a predictive hybrid strategy that fully charges the battery prior to the hill climb and the battery supplies the peak power demands, the sensitivity of the battery capacity to the fuel cell power is very high. If the fuel cell system would supply 200 kW at the wheels, the battery would need to supply almost 80 kWh at the wheels to complete the hill climb.

To narrow down the reasonable battery capacity, one must consider a more common use case, such as the VECTO cycle. Looking at the energy histogram of this cycle in Figure 2, a knee in the cumulated energy curve is evident at 265 kW. If the fuel cell system is sized to meet this power demand, the battery would need to supply 26.7 kWh of energy to complete the cycle. This energy would result in a total fuel cell system utilization in the VECTO cycle of 95%, or 92% in the "Brenner Alp Climb". Using this approach, a reasonable wheel power from the fuel cell system can be determined.

Since the previously determined power is the required power at the wheel, one must consider the additional losses and auxiliaries. In particular, the cooling fan must be considered since it can consume 15-20 % of the net fuel cell system power. The air supply system can consume another 10% of the system power. Furthermore, the fuel cell stack is subject to degradation and the loss in output power and efficiency must also be considered. This shift in load point and the increased waste heat is shown in Figure 3. The End-of-Life (EoL) polarization curve was determined using an FEV internal degradation tool.



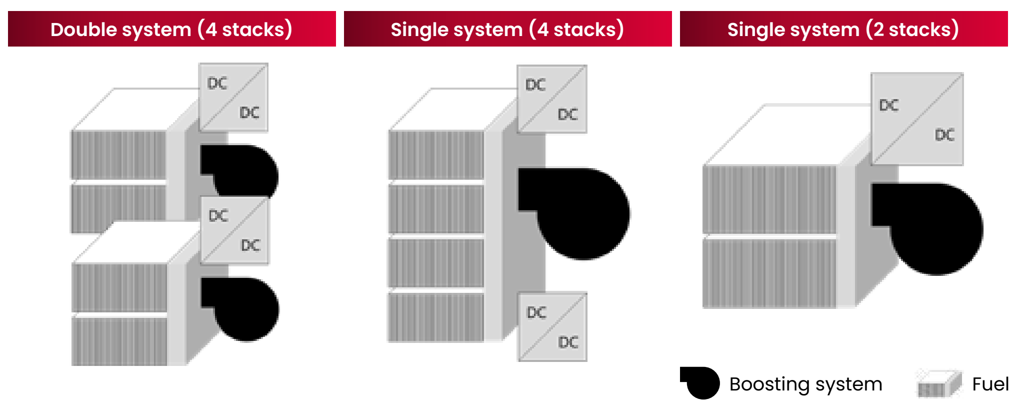
2.
Simulated histogram of energy at the wheel and cumulated energy demand of the "Brenner cycle" (top) and VECTO cycle (below) for a truck with 100% payload. Shaded grey area represents the energy to which the battery has to contribute in order to complete the VECTO cycle with a 265 kW fuel cell system.

Taking all these considerations into account together with a minimum required stack efficiency at EoL due to the thermal constraints a gross fuel cell stack power of approximately 380 kW is needed to meet the requirements of the heavy-duty truck.

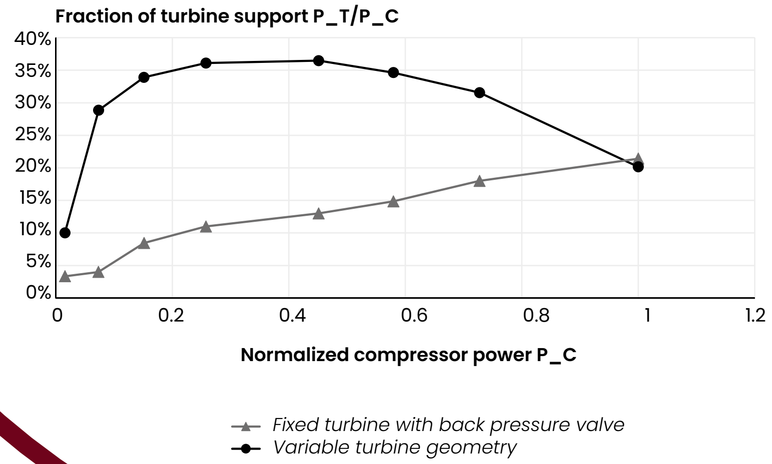
Since the fuel cell system must meet the high voltage architecture and safety of the vehicle additional considerations arise when designing a fuel cell stack and system layout. The required stack power is too high to enable a design with only one stack. Hence, the power must be distributed among multiple stacks. Multiple system configurations arise with different advantages and disadvantages in terms of performance, efficiency, economy of scale, and cost. Examples of such configurations are shown in Figure 4.

Double systems as shown in Figure 4 are beneficial for economy of scale due to the broader application. Single systems with four stacks can have advantages for the integration into the vehicle E/E architecture. One large single system has the highest efficiency potential but reduced economy of scale.

The differences in efficiency as well as cost are elucidated in the following:



4.
Modularization approach from multiple systems to a single system designt.



6.
Comparison of different turbine configurations.

Performance and efficiency

For the efficiency assessment of the different layouts detailed 1D-system simulations were carried out. The system simulation consists of the following sub-systems:

- Anode sub-system for hydrogen supply
- Cathode sub-system for air supply including a compressor-expander module (CEM)
- Physical model of the fuel cell stack
- Thermal management system to heat-up and cool the system

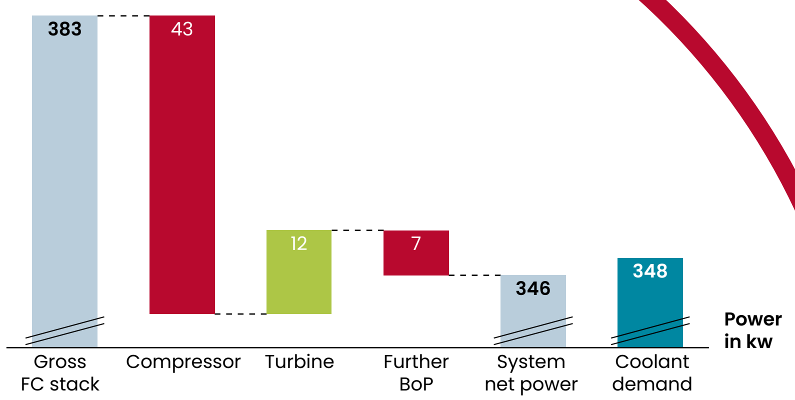
Within this system simulation the stack was scaled accordingly, and real component data was used for a realistic efficiency assessment. The component data was scaled as well with corrections for the component size.

High emphasis was put on the optimization of the CEM, since it is the largest consumer within the fuel cell system (FCS) boundary. Here, a study of different topologies was considered – fixed geometry turbine vs. a variable geometry turbine (VTG) and two small CEM vs. one large CEM.

The results of the simulation are shown in Figure 5. The largest consumer is the compressor with a power demand of 43 kW. The turbine can recover almost one third of the compressor power demand, leading to a peak power requirement of 31 kW of the CEM. The system efficiency of the fixed and variable geometry turbine system is equal at rated power. At part load, the system with VTG showed significantly higher efficiency due to the higher fraction of turbine support, see Figure 6.

When considering two small CEM versus a single large CEM, the larger one shows 4% reduced power consumption. Feeding back all these efficiency improvements into the cycle simulations, the fuel consumption can be decreased by more than 1.1% in the "VECTO cycle" and 1.6% in the "Brenner Alp Climb" cycle, when using a VTG system with a large CEM compared to a fixed geometry system.

5.
Result of the BoP optimization with variable turbine geometry at EoL



Cost reduction potential

Besides the technical impacts of a single FCS design, the cost reduction potential was also examined.

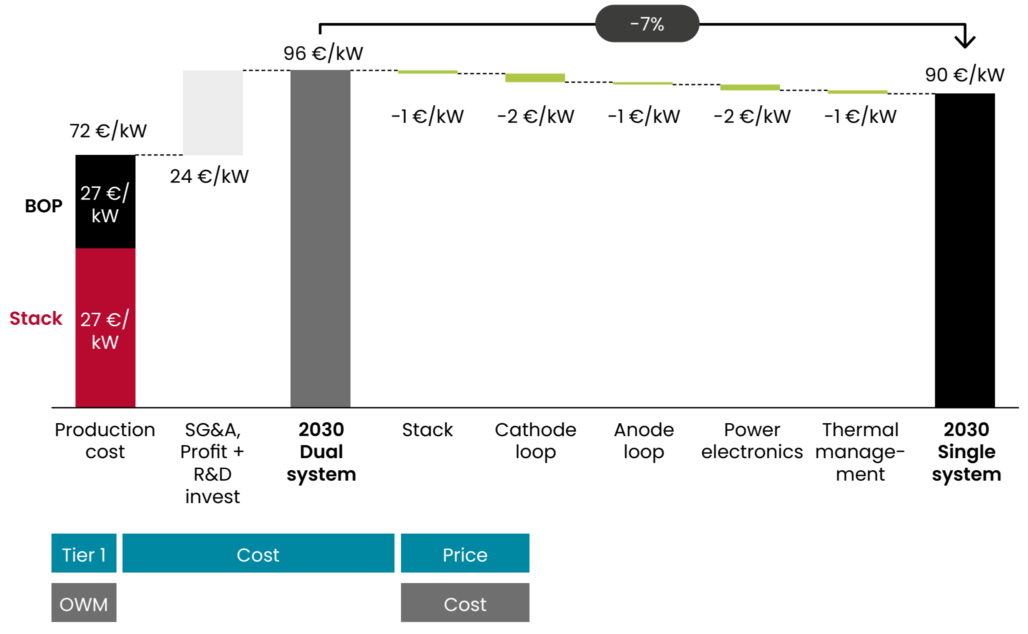
Based on studies and hardware benchmarks of several passenger car and heavy-duty truck fuel cell systems, a cost model was built for a generic dual system as a bottom-up should-cost approach with the following boundary assumptions:

		Boundary conditions
Production volume: Vehicles	Vehicles/year	15,000
Production volume: Dual System	Systems/year	30,000
Production volume: Single System	Systems/year	15,000
Production location	-	Europe

The production costs are calculated from the perspective of a Tier 1 supplier. Final stack assembly and system assembly are also considered to be done by a Tier 1 supplier, which sells the assembled system to the OEM: including a markup for SG&A, profit, and R&D costs.

The production costs are estimated at 72 €/kW_{net} for 2030, the markup leads to a price of 96 €/kW_{net} for an assembled system, see Figure 7, p. 44. This value is considered as a basis for the comparison between the dual system (two stacks each) and a single system solution (four stacks), see Figure 4. When costs are mentioned in the following, the procurement costs of the OEM are represented.

One single system instead of two parallel ones has a significant cost impact on most of the subsystems since duplicated are eliminated and for most components, cost does not strongly correlate with performance. The impact of reduced production volume due to this approach was considered as well.



7.
Cost reduction walk from a dual system to a single system with 345 kW_{net}.

While the costs for the cells within the stack as the main cost driver of the system remain the same, the costs for other stack components such as housings, manifolds or parts of the cell voltage monitoring (CVM) can be reduced in the single system approach. The assembly costs are also expected to decrease accordingly. These changes at the stack level reduce the system cost by about 1 €/kW_{net}.

The subsystem that benefits most from the single system approach is the cathode path. Here, main components that are considered twice in the dual system are replaced by a larger version in the single system. The CEM has already been mentioned above as an example. In addition, CEM inverters, charge air coolers, humidifiers, and different kinds of valves and sensors get cheaper. The cost for piping will also decrease. Overall, the cost of cathode components can be reduced by about 2 €/kW_{net}.

Similar effects reduce the costs for the components of the anode path by about 1 €/kW_{net}, whereby the costs for the recirculation pump, the water separator, the injector unit, the drain and purge valve, and the corresponding piping in particular can be assumed lower for the single system approach.

The main cost driver within the power electronics subsystem is the Fuel Cell DC/DC boost converter, which is also considered twice in the single system. However, other components such as the HV junction box, the HV and LV wiring and the FC control unit are estimated to be less expensive in the single system, having a cost reduction impact of about 2 €/kW_{net}.

»One large single system has the highest efficiency potential but reduced economy of scale.«

In the thermal management subsystem, the number of pumps, valves and sensors can be reduced in both the HT and LT circuits. These changes also result in less complex piping, so that the total system cost can be reduced by about 1 €/kW_{net}.

The sum of these effects reduces the expected cost for a single system in 2030 by about 6 €/kW_{net} to 90 €/kW_{net}, which means a reduction of 7% compared to the dual system (Figure 7). In a TCO calculation, this has a positive impact on the procurement costs of the vehicle. Furthermore, the efficiency benefits outlined in previous sections reduce the annual cost for hydrogen.

The largest driver for cost reduction is the limiting of cell numbers. With increased power density in the future, this number can be reduced, leading to further cost improvements for the CVM, housing, manifolds as well as DC/DC.

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Conclusion and outlook

This article has shown how to analyze the power requirements for HD fuel cell propulsion systems and how to size the main components of the propulsion system. The sizing of the fuel cell system, including FC stack and BoP, is presented in detail with a special focus on the CEM. Starting from today's fully modular approach to meeting FCS power requirements in HD applications, it is shown that purpose-designed single systems are more efficient and cost-effective than a dual system. The efficiency increases by 1.1 to 1.6% and the costs are decreased by about 6 €/kW for such 300+ kW_{net} FCS. Further cost reductions and improved power density can be expected for HD fuel cell stacks with significantly increased active area and nearly half the cells. With increasing sales of fuel cells for commercial vehicles, tailored fuel cell systems and stacks for heavy, medium and light commercial vehicles can be expected.

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