

## Sustainable Transportation



MAHLE is a leading international development partner and supplier to the automotive industry, with customers in the passenger car and commercial vehicle sectors. Founded in 1920, the technology group is working on the climate-neutral mobility of tomorrow, with a focus on the strategic areas of e-mobility and thermal management as well as further technology fields to reduce CO<sub>2</sub> emissions, such as fuel cells or highly efficient, clean combustion engines that also run on renewable fuels such as hydrogen. Currently the share of its sales earned independently from the internal combustion engine for passenger cars amounts to more than 60 percent. Half of all the vehicles in the world now contain MAHLE components.

In 2023, MAHLE generated sales of almost EUR 13 billion and is represented in 29 countries with more than 72,000 employees in 148 production locations and 11 MAHLE Tech Centers.

(Last revised: 2023-12-31)

#weshapefuturemobility



**Arnd Franz**

Chairman of the Management Board  
and CEO of the MAHLE Group

Dear readers,

Commercial vehicles are a crucial lever for a climate-neutral world. They keep the economy and its logistics chains running. No wind power plant or solar park can be built without the use of commercial vehicles. At the same time, the vehicles themselves must be clean and sustainable so that they meet legal regulations and climate requirements.

MAHLE has taken on this challenge from a technological perspective. In doing so, we keep a close eye on the fact that transport companies and fleet operators look at life cycle costs—i.e. the total cost of ownership. After all, the transport of goods must be economically affordable for them as well as for their customers and all of us, the end customers.

Our answer is technological diversity. In the three strategic fields of electrification, thermal management, and highly efficient sustainable combustion engines, we offer our customers technology solutions that contribute to climate protection while also meeting the most diverse market and customer requirements. In line with our “We Shape Future Mobility” vision, a good 72,000 MAHLE employees at 148 MAHLE locations worldwide are doing their best.

Our customer base includes more than 120 commercial vehicle brands in the on- and off-highway sector. That shows that our approach is successful, and that our products meet the requirements of the markets.

As you can see from the following pages, we offer technology expertise across the entire powertrain range. We electrify trucks, bring hydrogen engines into series production, participate in major fuel cell projects, and make the combustion engine fit for biofuels—we enable clean and climate-friendly mobility on and off road, by rail, and over water. Our products are tested and ready for series production, so we can tackle this all-important CO<sub>2</sub> reduction quickly and effectively.

I hope you enjoy reading this issue and discovering our latest technology innovations.

Arnd Franz



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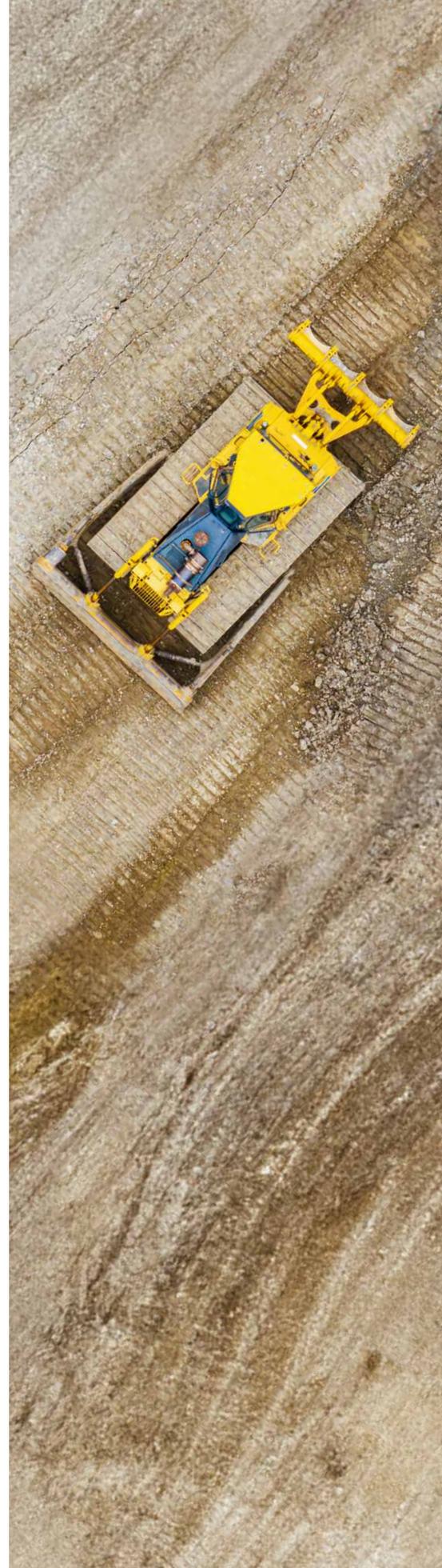
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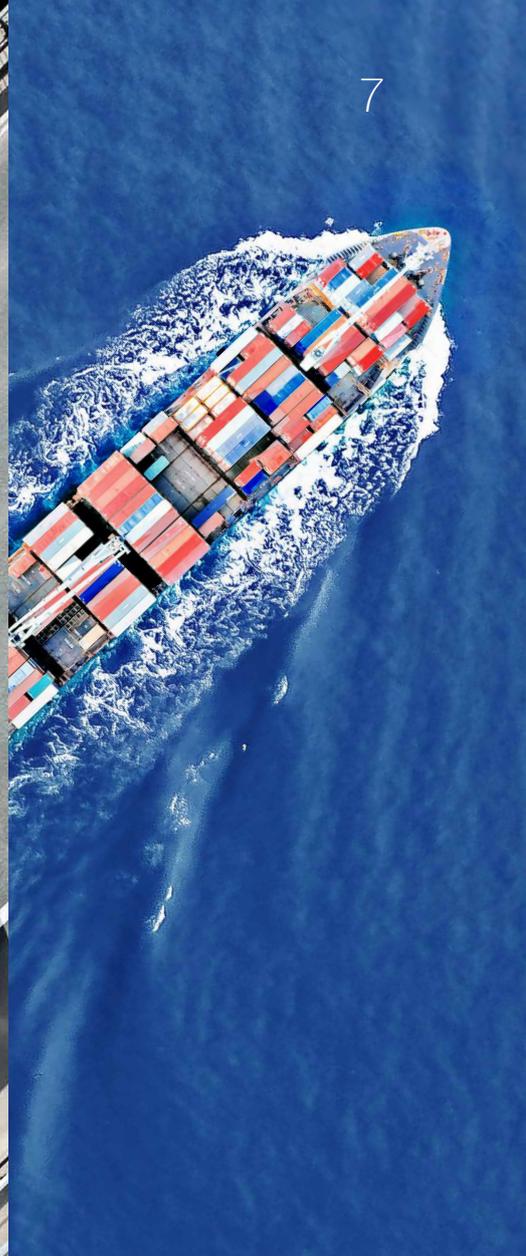
# Diversity for sustainable transportation

*The opportunities for climate-friendly commercial vehicles have never been more diverse. The technologies for all drive variants are developed for series production and ready to go in many fields of application. Which concepts will be most beneficial and where depends on local conditions.*

There is no way around decarbonization in the transport sector. Commercial vehicles make up 80 percent of freight traffic transporting our goods on land from A to B, and all forecasts predict growing transport volumes. The potential to reduce CO<sub>2</sub> emissions is just as great since 40 percent of the emissions generated by road traffic come from commercial vehicles.

The challenge of decarbonization can be found in the diverse range of applications it covers. Whether we're talking about parcel delivery and local distribution transport, or about regional transport, pan-European long-haul and heavy-duty transport, off-road applications or the transportation of people, each application on its own has very different profiles. And then there is also the cost factor as transport companies and fleet operators take life cycle costs into account because the transportation of goods must be profitable. For that reason, MAHLE developers are working on the right drives for different regions and framework conditions. We have summarized the advantages of the concepts on the following pages.





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We supply our customers with climate-friendly products that are ready for use and in series production in many places—for all regions, vehicle classes, applications, and fuels.

**Matthias Fix**  
Vice President Sales & Application  
Engineering Commercial Vehicles



## Battery electric for short haul

For local and distribution transport, all the signs are pointing to battery electric mobility. This trend is being accelerated by metropolitan regulatory requirements on noise and exhaust emissions. Then there is also a social trend as modern consumers expect things to be ordered now and delivered immediately. This not only applies to classic e-commerce. Other delivery services are also contributing to this development. They bring daily necessities to your doorstep within minutes.

This has an impact on the retail sector as electric vehicles will take over transporting the products from the distribution warehouses. “MAHLE supplies the right components for electric drives and thermal management systems for all variants of electric vehicles,” explains Sales Manager Matthias Fix.

Delivery vehicles returning to the depot after their round use their own charging infrastructure. This is where MAHLE steps in to provide a solution for the transportation and logistics industry with its chargeBIG charging management system. With enough cruising range for a whole working day, the battery-electric combination is gaining ground.



## Hydrogen for long haul

For long-distance hauling, however, the trend is different. Here, battery-electric drives hit their limits when it comes to cruising range and weight. Hydrogen could prevail here as a practical energy storage medium. Electrical energy drives the vehicle in this case too, but it is only generated during the journey when gaseous hydrogen and atmospheric oxygen come together in the fuel cell. This type of drive makes the tractors lighter, so they can transport more payload. Even when it comes to the cruising range per tank of fuel, the combination of hydrogen and fuel cell has the edge.

The hydrogen combustion engine is also a particularly interesting option for long haul. It doesn't need a battery as the hydrogen is burned like a fossil fuel. This saves weight and also ensures a longer cruising range. An additional advantage is that conventional combustion engines can be converted to run on hydrogen. Both hydrogen technologies require sufficient refuelling infrastructure for heavy-duty freight transport because existing hydrogen filling stations are usually not designed for heavy-duty trucks. A further challenge is posed by the availability of “green hydrogen,” which is produced by climate-neutral means through electrolysis with electricity from wind, solar or hydropower. However, there still aren't enough appropriate plants in Germany to produce it on an industrial scale.

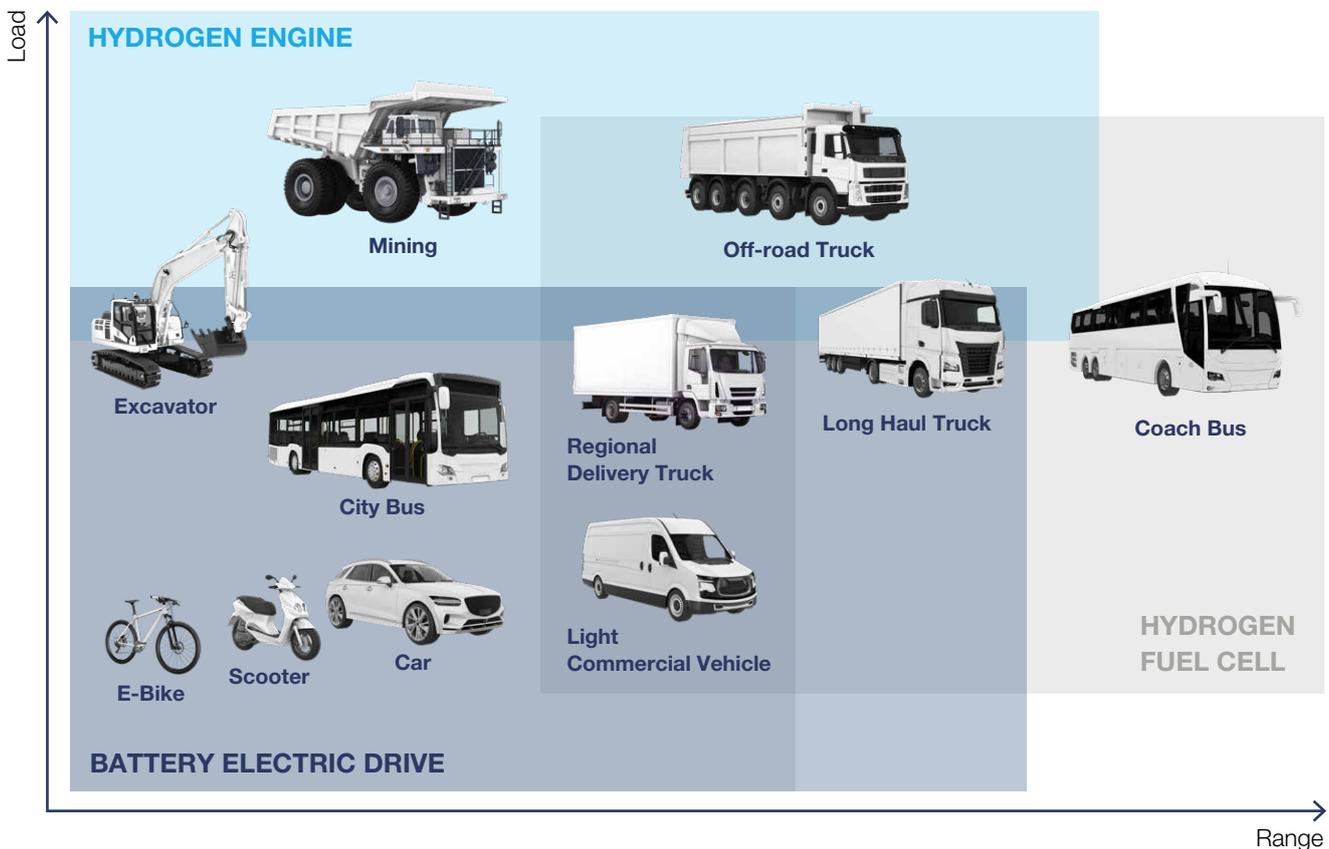


## Climate-neutral faster: clean combustion engines

The transport industry is currently in a phase of transition and open to new technologies. Battery-electric commercial vehicles are already in daily use, and the first fuel cell trucks are already being tested in practice. But there are other alternatives that can contribute to rapid decarbonization. E-fuels produced with green electricity as well as hydrogen for internal combustion engines allow vehicles with significantly lower CO<sub>2</sub> emissions to continue to be used. This also applies to existing fleets. What ultimately prevails in long-distance hauling is still unclear, and this is precisely why MAHLE is calling

for technological diversity. "With this holistic approach, we provide the right solution for each vehicle class, the intended application of the vehicle, and the region in which it is to be used," says Matthias Fix. Many regions of the world still won't have sufficient infrastructure to charge batteries or produce or refuel with enough green hydrogen for years to come. For these regions, MAHLE is developing systems and components for highly efficient, low-emission combustion engines. These will not only be used in logistics, but in agriculture too, for transportation by both rail and sea.

## The future of mobility will be more diverse



## MAHLE 2030+

*Our strategy focuses on three strategic fields: electrification, thermal management, and efficient and clean combustion engines.*

Even if the future of mobility is electric, clean and efficient combustion engines will continue to be part of the drive mix. These are especially sustainable if they run on hydrogen, or synthetic or bio-fuels. What does this mean for MAHLE? Which product portfolio can MAHLE use to shape sustainable mobility and in which markets can it operate successfully? The answer to this is our strategy MAHLE 2030+. It is our orientation for the path to a sustainable future.

Mitigating man-made climate change is a top priority and requires a drastic reduction in CO<sub>2</sub> emissions. For the mobility sector, this means a change toward elec-

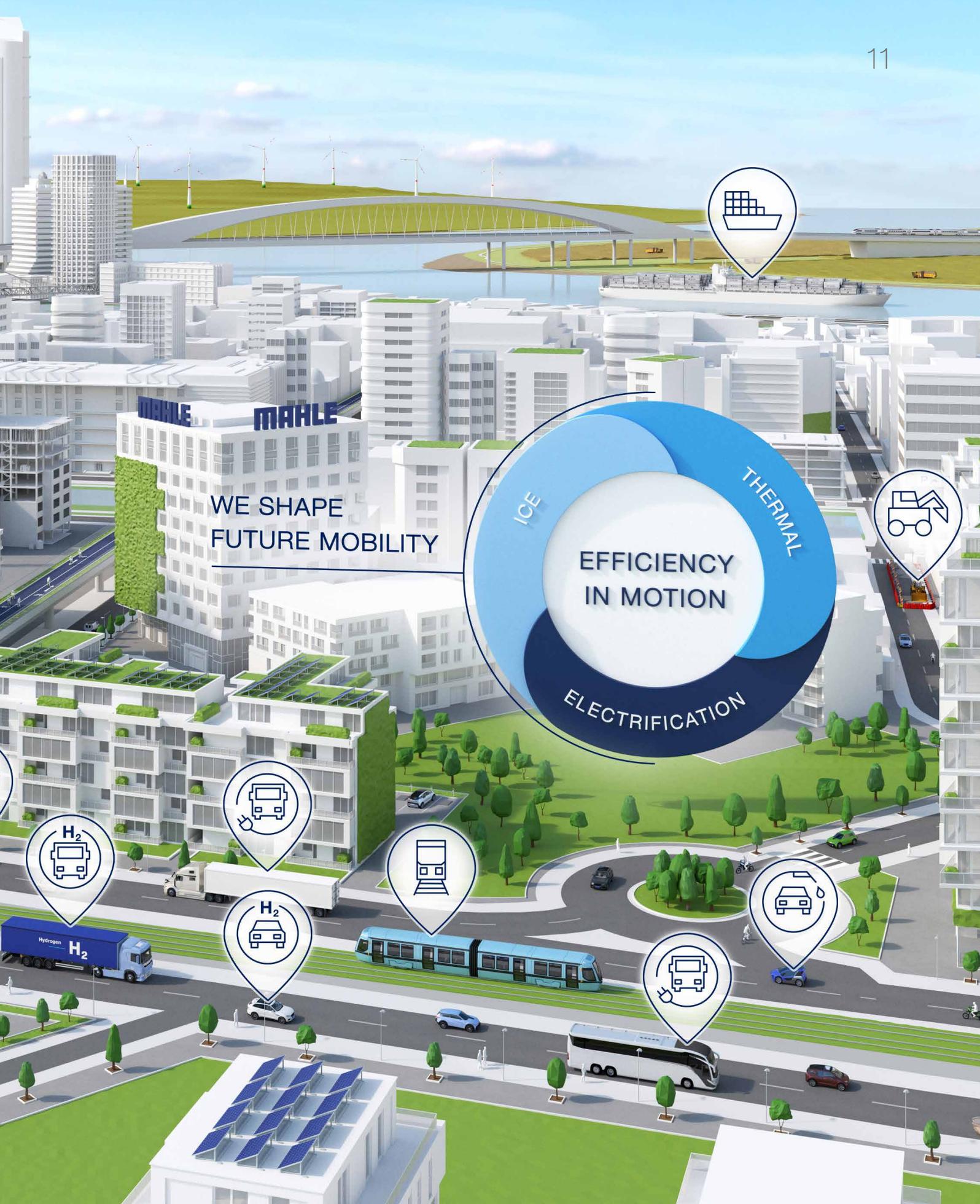
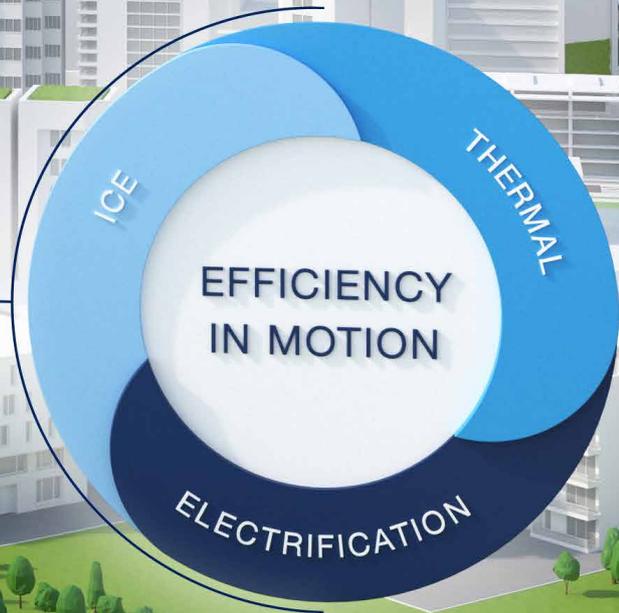
trified drives. As a result, the automotive industry is experiencing one of the most far-reaching transformations in its history.

MAHLE is playing a crucial role in the transformation of the automotive industry and will take advantage of its opportunities. The combination of the three strategic areas of electrification, thermal management and efficient combustion engines makes MAHLE unique in the automotive supplier industry. MAHLE will concentrate on those products with which the company already occupies a leading market position today or with which it can assume one tomorrow.

All MAHLE activities have one thing in common: maximizing output while reducing emissions. Efficiency for everything that moves. So that's our vision: "Efficiency in Motion."



WE SHAPE  
FUTURE MOBILITY



# MAHLE on site

*148 production locations*  
*11 MAHLE Tech Centers*  
*72,373 employees\**

## MAHLE Tech Centers

### Europe

Stuttgart/Germany (Bad Cannstatt, Feuerbach, Fellbach, Kornwestheim, Markgröningen, Schorndorf)

Valencia/Spain

Šempeter pri Gorici/Slovenia

Northampton/Great Britain

### North/South America

Detroit/USA (Troy, Farmington Hills)

Lockport/USA

Jundiaí/Brazil

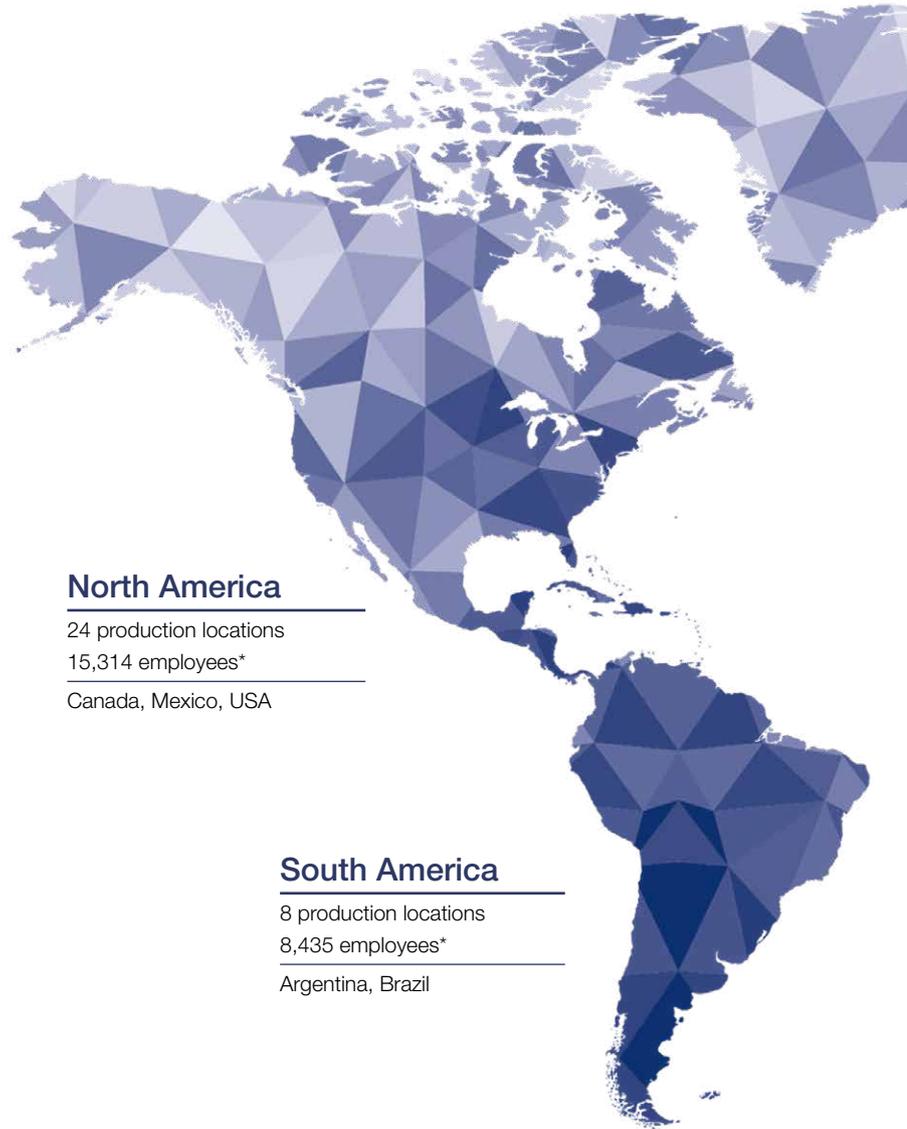
### Asia/Pacific

Pune/India

Shanghai/China

Changshu/China

Tokyo/Japan



### North America

24 production locations

15,314 employees\*

Canada, Mexico, USA

### South America

8 production locations

8,435 employees\*

Argentina, Brazil

## Europe

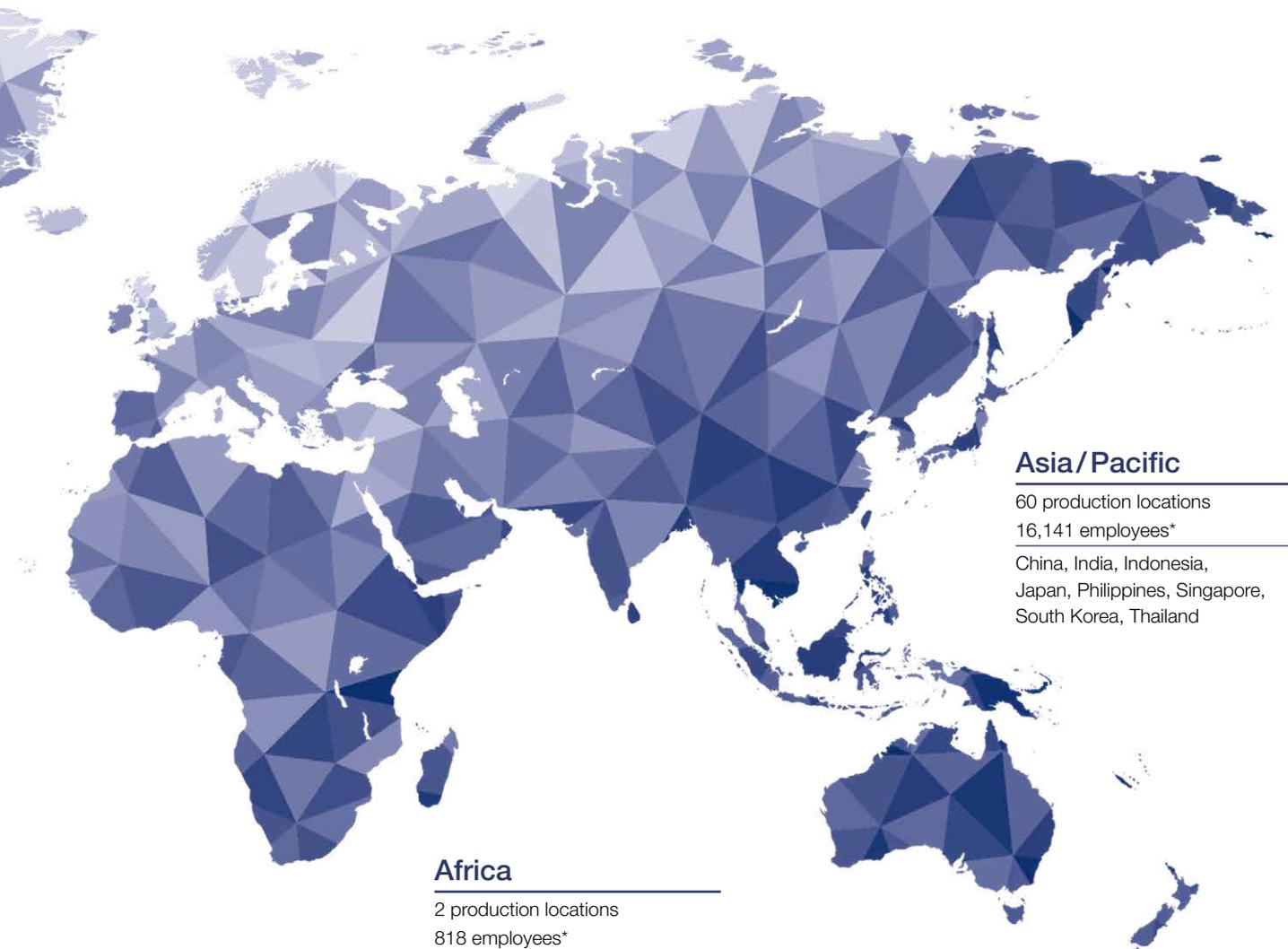
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54 production locations

31,690 employees\*

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Austria, Bosnia and Herzegovina, Czech Republic, France, Germany, Great Britain, Hungary, Italy, Poland, Portugal, Romania, Slovakia, Slovenia, Spain, Türkiye



## Asia/Pacific

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60 production locations

16,141 employees\*

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China, India, Indonesia, Japan, Philippines, Singapore, South Korea, Thailand

## Africa

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2 production locations

818 employees\*

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South Africa

## HYDROGEN PROPULSION

# Long H<sub>2</sub>aul

*Fuel cells are particularly suitable as a climate-neutral powertrain technology for long-distance journeys: the Long Haul. Dr. Marco Warth explains the MAHLE approach to development and what is important when converting hydrogen into electricity.*

**Dr. Warth, what distinguishes MAHLE when it comes to developing components for fuel cell vehicles?**

What's crucial here is our systems expertise. This doesn't mean that we develop everything ourselves, but we have a comprehensive understanding of the components we do make—from sub-modules to drives—and can also derive the boundary conditions accordingly. This is borne out by the latest model from our systematic approach to a fuel cell truck, which consists of a heavy-duty E-axle in which we have compactly integrated two SCT electric motors with a total output of 520 kW as well as the complete liquid management system. There is also the MAHLE battery cooling and our fuel cell peripherals for everything related to fuel cells. Another highlight is sure to be our new evaporative cooling system,



Head of MAHLE Corporate Research and Advanced Engineering

which also ensures the optimum temperature of the fuel cell. This means less fan performance is required and hydrogen consumption is reduced by up to 1.5 percent.

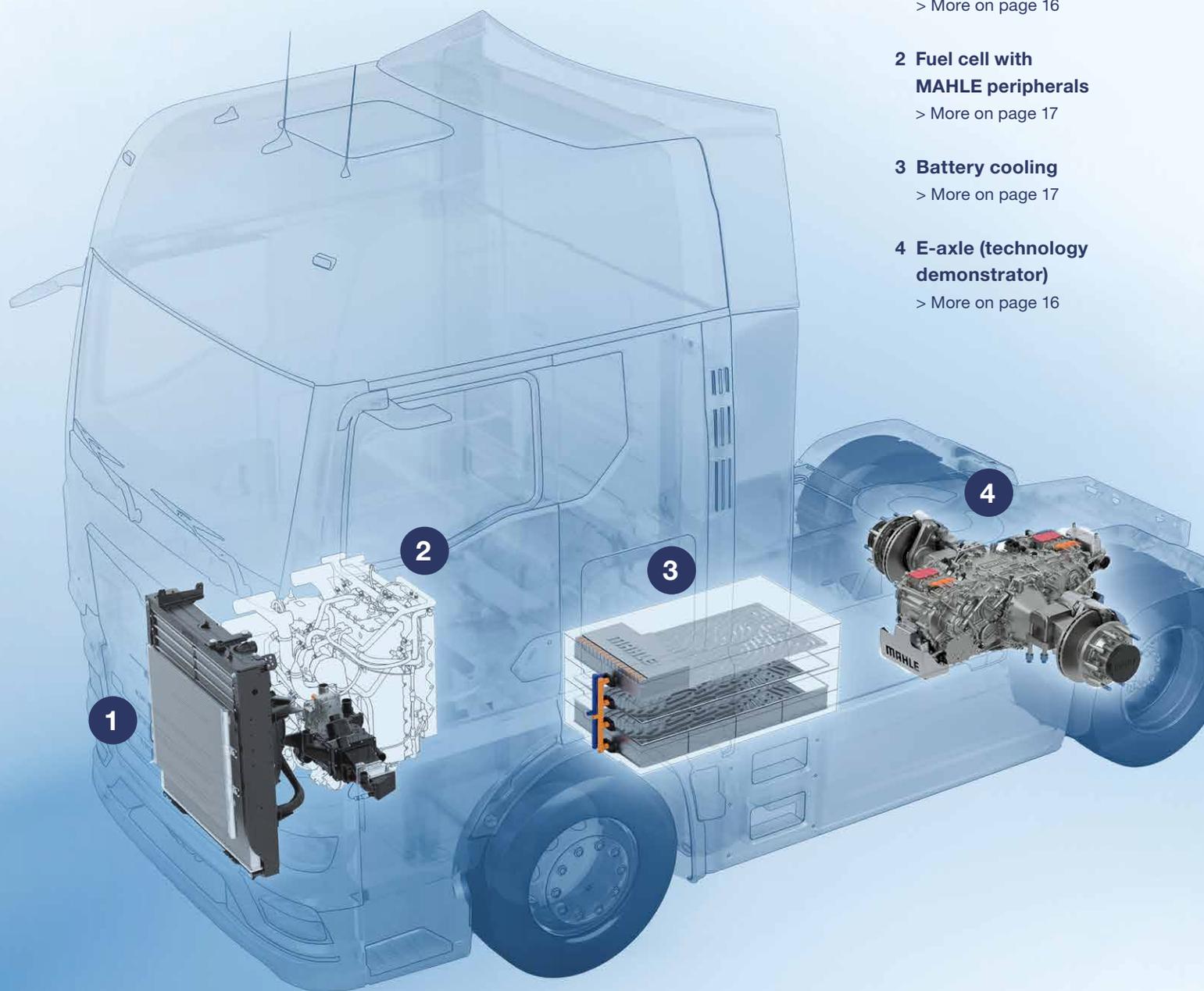
**What are the benefits of our systematic approach for customers?**

Our products are developed, tested, and ready for series production application in the system. We can integrate our technologies, including thermal management, into electric vehicles and therefore optimize a wide range of options for different customer applications. That this is highly appreciated is also reflected in the fact that MAHLE is involved in all current development projects for fuel cell vehicles and major hydrogen engine projects.

**What potential do you see for fuel cells in commercial vehicles?**

According to predictions, purely electric trucks with batteries and fuel cell trucks will account for around 30 percent of global production in 2035.

While battery-electric drive systems are mainly used in the medium-duty truck segment and in the heavy-duty range on short-haul routes, the fuel cell comes into its own in terms of its advantages on long-haul routes. It scores with a good ratio of cruising range per tank of fuel. On long-haul routes, it will be used alongside combustion engines powered by hydrogen and other renewable fuels.

**1 Cooling module**

> More on page 16

**2 Fuel cell with  
MAHLE peripherals**

> More on page 17

**3 Battery cooling**

> More on page 17

**4 E-axle (technology  
demonstrator)**

> More on page 16

# Team fuel cell

*The fuel cell is an effective lever for the decarbonization of commercial vehicle transport. However, the drive places the highest technical demands, especially on its peripherals.*

## Cleverly tempered

Compared to the significantly hotter internal combustion engine, the temperature difference to the outside temperature in a fuel cell is smaller. This poses a greater challenge for the cooling system and that's where the systematic approach of MAHLE comes in.

The new evaporative cooling system sprays water onto the radiator via a grille. The cooling effect of the evaporating water is so great that up to 50 kW more cooling capacity can be provided in the same package constraint. Hydrogen consumption is also reduced by up to 1.5 percent.



## E-axle with system

The MAHLE E-axle is a technology demonstrator MAHLE is using to demonstrate its systems expertise in the electrification of heavy-duty commercial vehicles. Two MAHLE SCT electric motors (p. 18) with a total peak power output of 520 kW and a continuous output of 480 kW are integrated into the E-axle.

The highly integrated liquid management module is part of the overall solution. This extremely compact component cools electric motors extremely efficiently and with the lowest pressure loss. In a heat exchanger, the heat from the oil is transferred to the coolant circuit. The oil filter and the oil pump are already integrated into the module. Both the SCT electric motors and the SCT liquid management module are developed and ready for series production.

Whether it's purely battery-powered electric drives, hybrid drive forms, or fuel cell drives, MAHLE offers the right electric oil pump for every application. The oil pump family from MAHLE is scalable in terms of power output as well as the number of suction and pressure stages. Therefore, outputs of up to 250 watts are possible. MAHLE offers a choice of 12 V and 24 V systems (48 V on request).

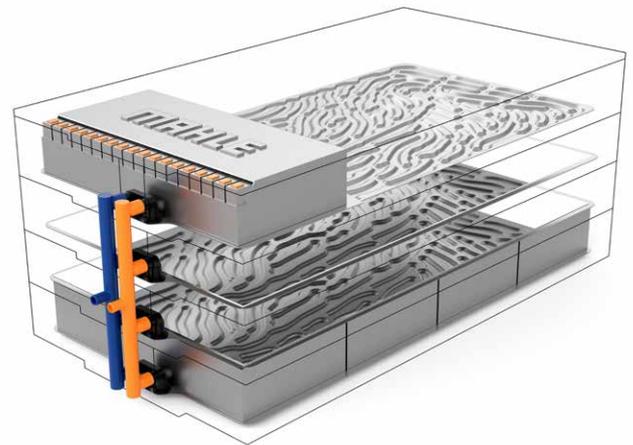
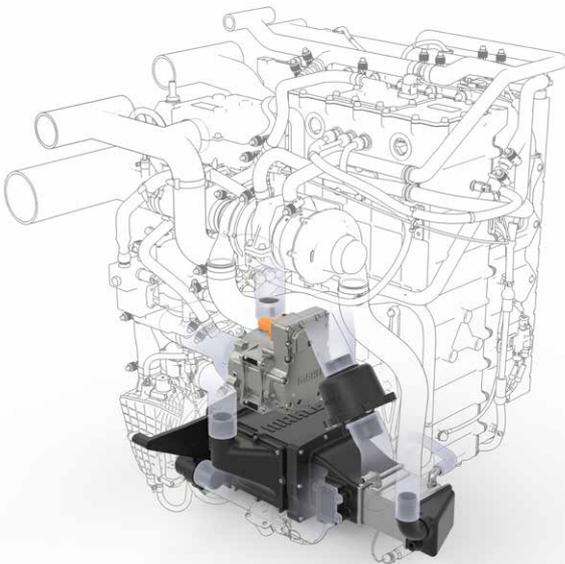
### Efficient peripherals

The MAHLE peripherals, consisting of a charge air cooler, flat membrane humidifier, water separator, and high-voltage pump, increase efficiency, protect the cell from premature aging, and allow it to operate at a higher temperature. The result is more output and improved efficiency, which is made possible by a 50 percent reduction in pressure loss in the air pathway of the fuel cell.

The MAHLE 800 V high-performance coolant pump achieves up to 2.5 kW of output and can move 300 liters of coolant per minute at 2.5 bar. An important detail: The coolant is protected from being mixed with ions, which would generate undesirable electrical conductivity.

In order to function optimally, fuel cells require humidified air kept at a constant, precise temperature throughout their entire service life. A flat membrane humidifier, filters, and charge air cooling take care of this. The MAHLE developers have brought all these players together in one cathode module. This systematic approach reduces costs.

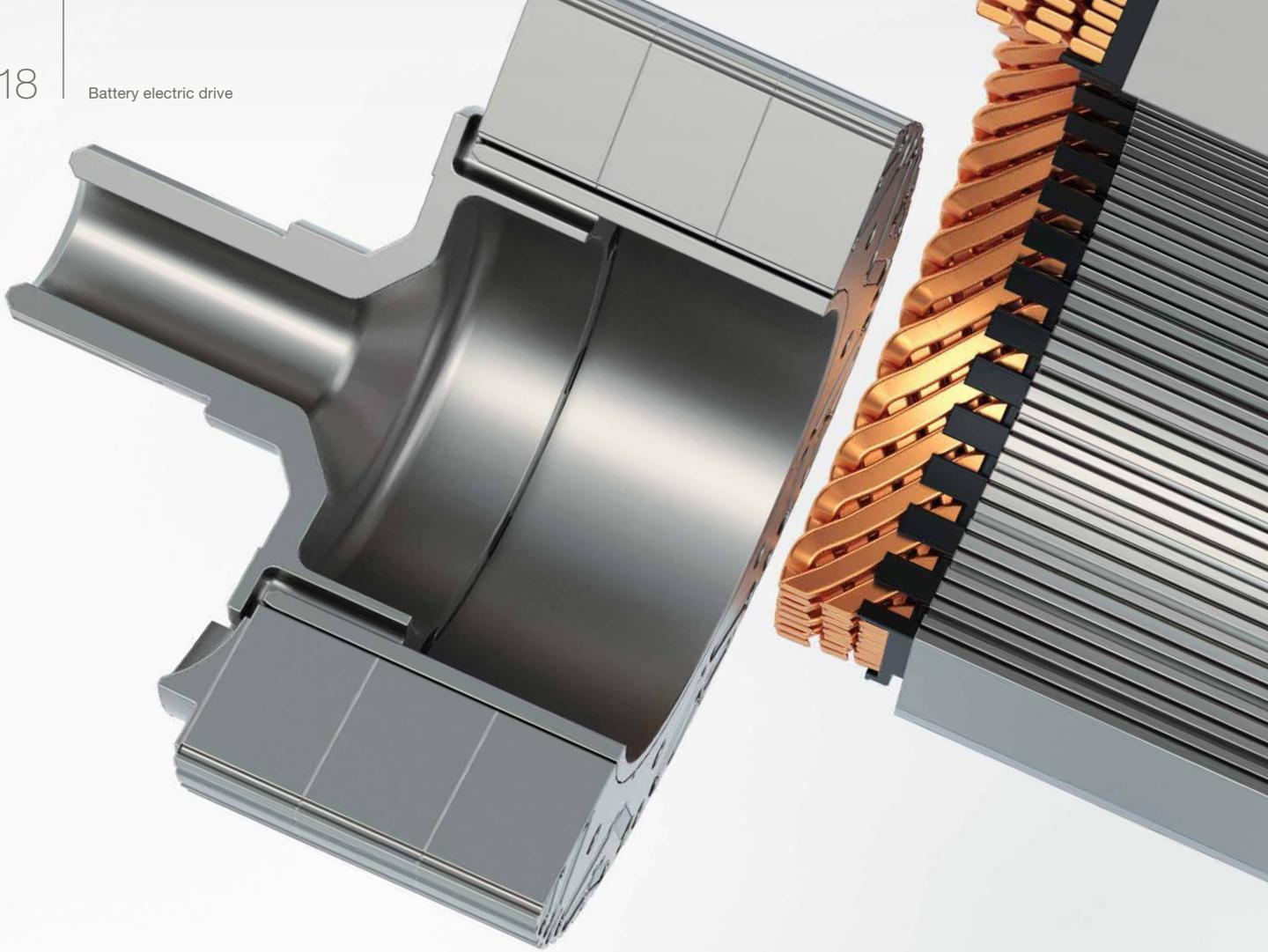
The air compressor in the fuel cell system must be protected from the impact of droplets from the fuel cell exhaust air. The MAHLE water separator uses its inertia to do this as the air is accelerated in a rotor and the water is separated by centrifugal forces.



### Uniquely cooled

The sensitive fuel cell must constantly be kept cool. To avoid damaging the fuel cell, the coolant must not be electrically conductive. In the MAHLE coolant-to-coolant cooler, the heat from the fuel cell's coolant is therefore transferred to the powertrain's coolant, which prevents the fluids from mixing and becoming conductive. This allows the volume of the fuel cell cooling circuit to be kept as small as possible.

In the MAHLE cooling circuit, the coolant in the battery module takes a path that is unique worldwide. The reason is the bionic cooling plate design (p.26), which imitates flow patterns found in nature. The fluid channels through which the coolant flows are modeled on corals. The plate therefore delivers ten percent more cooling capacity than conventional designs. It also enables the battery to charge faster.

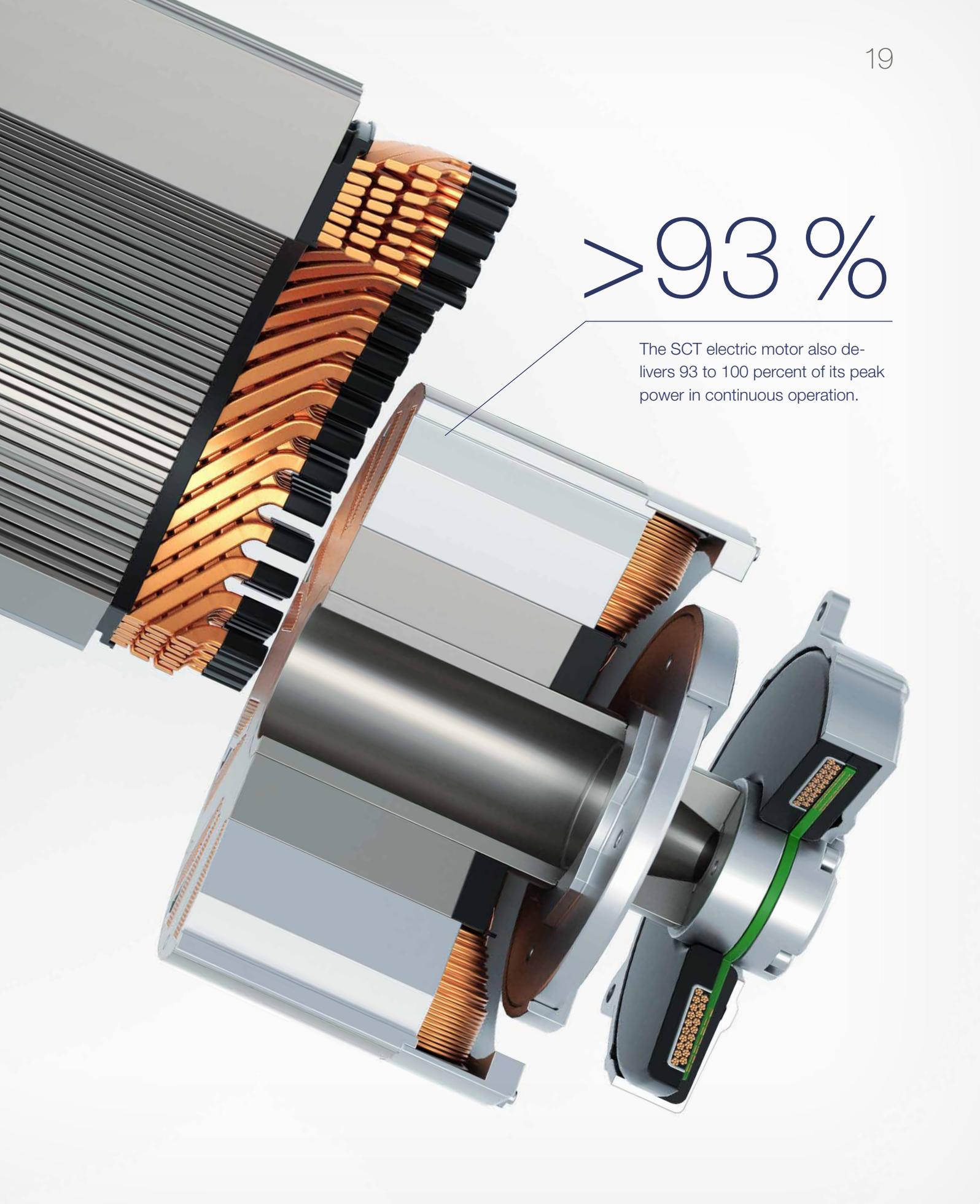


## BATTERY ELECTRIC DRIVE

# Customized modular system

Systems expertise is a crucial factor in the push to further develop electrification technology. The interaction of individual components in electric drives is much more complex than in internal combustion engines. MAHLE has developed a modular technology system that exploits this strength to develop even more powerful electric motors. The modular system combines the advantages of the company's two electric motors: the MCT (Magnet-free Contactless Transmitter) and the SCT (Superior Continuous Torque). The MCT electric motor stands out for its high durability. The necessary transmission of the electric currents between the rotating and stationary parts inside the motor is contactless and, therefore, wear-free. This makes the motor maintenance-free and suitable for a variety of applications. The SCT electric motor means MAHLE currently

has the most enduring electric motor in the range. The electric motor is unrivalled in terms of its small size, light weight, and efficiency. Nevertheless, it can operate at high power for an unlimited time; its continuous power output (480 kW) is an impressive 93 to 100 percent of its peak power (520 kW), as evidenced by test results. In addition, MAHLE electric motors do not require any rare earth elements, which not only makes them more environmentally friendly to manufacture, but also brings advantages in terms of costs and raw material supply security. The MAHLE modular technology system enables customers to combine the advantages of MCT and SCT electric motors and benefit from customized electrification solutions from MAHLE for every vehicle class, every application, and in accordance with their respective brand philosophy.



> 93 %

The SCT electric motor also delivers 93 to 100 percent of its peak power in continuous operation.

# Wireless charging — simple and convenient



The current features of smartphones will soon make it easier for electric vehicle owners to charge their batteries: inductive charging. Siemens is developing the infrastructure, and MAHLE is handling the automotive engineering and the user-friendly positioning system. A “transmitter” coil is placed at the bottom of the garage or parking space for this. If a vehicle parks on it, a magnetic field is generated and transmits the energy to the “receiver” coil in the car. The battery charges with a charging power of 11 kilowatts and a 92 percent efficiency—and without cables! The MAHLE positioning system works in compact passenger cars as well as in large commercial vehicles and was declared as the global standard by the SAE in 2023.



Receiver coil for mounting on the vehicle

# Climate-neutral fleet: smallBOX instead of wallbox

*The chargeBIG charging system is the ideal charging solution for electric and hybrid fleets in compliance with calibration law. Thanks to integrated sub-distribution and load management, the smallBOX is ideally suited for transport and logistics companies.*



The chargeBIG charging infrastructure is unique due to its centralized approach. This means that significantly more charging points can be created at one location than with conventional charging solutions. Sub-distribution and dynamic load management are therefore an integral part of the charging solution and enable simple installation, maintenance and high scalability.

The centralized concept is not only smart, but also sustainable. Compared

to conventional charging solutions, up to 50% fewer cable resources are used and, thanks to load management, each smallBOX only uses the power that the grid connection releases. This avoids voltage peaks, switching to more expensive electricity tariffs and expanding the grid with a new transformer.

Once at the parking lot, the user experiences ease of use and a unique charging experience. Via the propri-

etary chargeBIG app and the payment terminal, chargeBIG offers generatable activation codes and charging cards for cost center and vehicle-specific billing. chargeBIG has a suitable charging solution for every area of application.

The chargeBIG smallBOX is also ideal for electrifying employee parking spaces at company locations. This creates incentives to switch to an electric or hybrid vehicle and actively participate in the mobility transition.

## THERMAL MANAGEMENT

# Well tempered

*No matter whether a motor provides propulsion through combustion or electricity, the supply and dissipation of heat play a crucial role. For commercial vehicles, MAHLE offers an integrated thermal management system for every drive and place of application.*

Internal combustion engines should warm up as quickly as possible, but must not overheat. Battery electric engines have a narrow temperature range, which ensures a longer service life for the components, greater cruising range, and better fast-charging capability. Fuel cells require complex cooling systems and large coolant coolers with higher total waste heat. And then there's the issue of comfort: the vehicle should not be too hot in summer but should be nice and warm in winter. Quite a lot of that is down to thermal management.

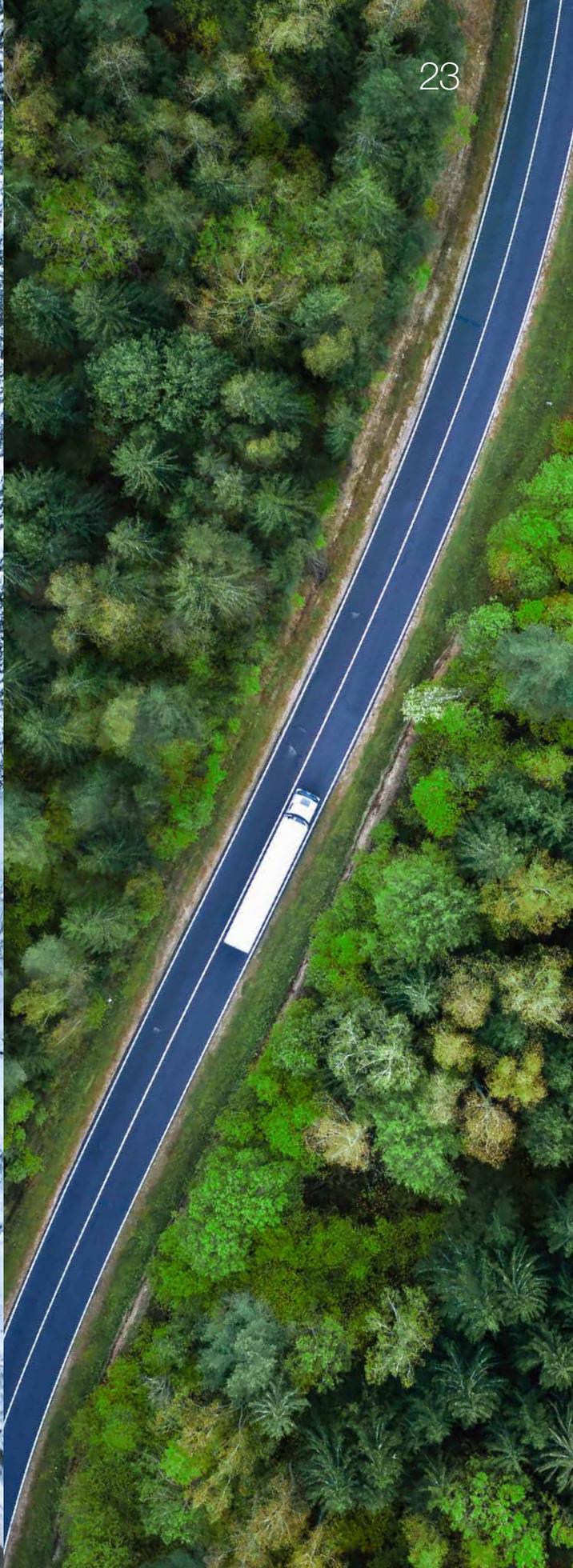
## Key technology

Thermal management is a key technology for the transition to zero-emissions drives. Especially in battery electric drive systems (battery electric vehicles, BEV) and those with a fuel cell (fuel cell vehicles, FCV), the demands are sometimes two to three times as high compared to internal combustion engines.

## For every application

What makes thermal management in the commercial vehicle sector even more demanding are the different regions, vehicle classes, and applications. In order to still keep the package, complexity, and costs as small and low as possible, MAHLE combines the components of the thermal management system in compact modules. MAHLE offers scalable thermal management: from delivery vans to heavy-duty commercial vehicles, from European markets through to the streets of Asia.





# Ready for the right temperature

## A quiet world-first: the bionic fan

Extremely quiet and bionically optimized. In developing this new high-performance fan, the engineers at MAHLE were inspired by owls' wings. The edges of the fan blades have been modeled on the feathers of these birds of prey, which are well known for being barely audible in flight. This solves another challenge for e-mobility: loud fan noise, which can be

disturbing at full load as well as when charging the vehicle at night in residential or rest areas. The MAHLE bionic fan is up to 4 dB(A) quieter than comparable fans, which is equivalent to more than halving the sound output. At the same time, the device has improved efficiency by 10 percent and reduced weight by 10 percent.

# >50 %

The new bionic fan from MAHLE is more than half as quiet as comparable devices.



### 800-volt PTC heater—Comfortable temperatures, even in the cold season

Battery electric vehicles lack the heat from the combustion for interior heating in the cold season. Here, a highly efficient heat pump can often provide pleasant interior comfort. But every now and then, additional heating must be provided electrically. The 800-volt PTC heater from MAHLE heats the interior air directly. This is fast and highly efficient, with up to eight kilowatts of heating power.



### 800-volt e-compressor—The heart of thermal management

The e-compressor is important for the temperature control of the e-drive and thus crucial for the service life, high charging speed and range of the battery. It also ensures the high level of interior comfort and pleasant interior acoustics. MAHLE currently offers its extremely compact high-voltage compressor in voltages of up to 900 volts, displacements of up to 57 cubic centimeters and outputs of up to 18 kilowatts. Its compact design, combined with its high performance, means that it can be used in all vehicle classes—from passenger cars to heavy commercial vehicles.



### Systemically integrated: the Cooling Module

Cooling Modules protect batteries and power electronics by releasing much of the heat built up in the system into the environment. Depending on the cooling strategy, the modules could include additional radiators. For over 100 years, MAHLE has been playing a crucial role in advancing development, from simple coolers to complex thermal management.



### Inspired by nature: the bionic battery cooling plate

The MAHLE bionic battery cooling plate keeps the lithium-ion battery in the optimal temperature range between 10°C and 40°C at all times. Inside the cooling plate, the coolant flows through fluid channels. In this innovation, the channel design imitates flow patterns found in nature. This reduces pressure loss by up to 20 percent and at the same time increases the cooling capacity by 10 percent. It also enables faster charging of the battery and helps extend the service life of the battery.



### Complex system for efficiency and comfort: the Air Conditioning System

MAHLE's highly efficient Air Conditioning System ensures the cabin is perfectly climate-controlled while minimizing energy consumption. Working in a pleasant temperature, drivers can focus better and safely navigate the traffic. In addition, the CareMetix® Cabin Filter keeps the cabin free of fine particulates and pollutants, thus protecting the driver's health.



### Coolant-to-Coolant Cooler for Fuel Cells

The fuel cell is the heart of the fuel cell drive. It must be constantly cooled. However, the coolant must not be electrically conductive, otherwise the fuel cell will be irreparably damaged. In MAHLE's coolant-to-coolant cooler, the heat is therefore transferred from the coolant of the fuel cell to the coolant of the powertrain without mixing, which would make it conductive. This also allows the volume of the fuel cell circuit to be kept as small as possible.



### Indirect Heat Exchangers

Increasing comfort in the passenger compartment and the development of new drive systems are leading to steadily rising demands on thermal management. At the same time, the installation space required for this in the vehicle is and remains limited. The indirect heat exchangers from MAHLE can be installed where they are needed in a space-optimized manner. Here, two refrigerant or coolant circuits that are decoupled from each other intersect. Cooling takes place via the coolant coolers in the cooling module. An additional direct heat exchanger in the module is therefore no longer necessary. The length of the coolant lines can be kept as short as possible and thus the amount of refrigerant or coolant can be kept as low as necessary.



### Highly integrated systems competence: the Oil Management Module

The traction motor is a “powerhouse” that has to be protected against overheating. MAHLE’s integrated and compact Oil Management Module cools the motor, with a Heat Exchanger transferring the heat from the oil to the coolant circuit. The Oil Pump needed for this is already integrated into the module.



### High-performance coolant pump for fuel cell applications

The fuel cell requires a high cooling capacity. The 800 V high-performance coolant pump from MAHLE delivers up to 2.5 kW of power and can pump 300 liters of coolant per minute at 2.5 bar. The pump could fill two bathtubs at a height of 25 meters in one minute. The 5 kW version could deliver even up to 500 liters per minute. At the same time, it must not be contaminated with ions in order to prevent undesirable electrical conductivity of the coolant



## MOBILITY THOUGHT HOLISTICALLY

# Unlocking potential

*The fastest way to decarbonize the commercial vehicle sector is through technological diversity. This means that, in addition to batteries or fuel cells, hydrogen and other alternative fuels in the internal combustion engine can play a major role on the way to climate-friendly transportation. MAHLE has already developed and tested the right technologies for series production.*



Another way to reduce CO<sub>2</sub> emissions in road transport is to use hydrogen as a combustion fuel. In the process, hydrogen and oxygen are used in a similar way to diesel in a conventional combustion engine, for example. MAHLE is using its 100 years of expertise in combustion engines to optimize its components for climate-neutral operation on hydrogen. All parts are further developed using a holistic approach, so that the engines are able to use carbon-free fuel highly efficiently and with a long service life.

#### **For high performance and heavy loads**

The lower peak pressures when using the gas makes it possible to use aluminum instead of steel as a material. Nevertheless, there are some challenges as the gaseous hydrogen is contained in a high-pressure tank. During its combustion in the pistons, a small proportion of the gas gets into the crankcase. The housing must be ventilated so that this so-called blowby gas does not ignite. The MAHLE optimized power cell unit reduces blowby to a minimum. Another challenge is that all components must function without the self-lubricating characteristics of diesel fuel.

In addition to e-mobility, e-fuels offer enormous potential for cutting carbon emissions.

With the right engine technology, hydrogen has the potential to make heavy-duty and off-road applications climate-neutral quickly. Hydrogen-powered engines are particularly suitable for high load cycles with sudden load steps and can withstand heat, dust, and vibrations.

#### **Upgrading existing technologies**

The role of synthetic fuels or biofuels (HVO100) should not be underestimated until synthetic fuels are more widely available. They can make an additional contribution to the reduction of carbon emissions in the transportation sector. Some regions, such as South America and India, rely entirely on biofuels.

MAHLE optimizes existing components to make combustion engines of all kinds even more efficient. Lower temperatures at the piston rim allow for hotter and more efficient combustion, and variable oil pumps reduce consumption. Reduced-friction cylinder liners, innovative piston rings, and more robust camshafts with special coatings allow low-viscosity engine oils to be used with the same wear and tear. In addition, corrosion-resistant valves allow higher exhaust gas recirculation rates, and polymer-coated bearing bushings ensure minimal friction.

Hydrogen as a combustion fuel has the potential to make heavy-duty and off-road applications climate-neutral quickly.



**RESEARCH & DEVELOPMENT**

# Developing the future

MAHLE takes a holistic approach to research and development. The MAHLE development centers are based near the world's most important locations in the automotive industry and combine development with testing expertise. Products can therefore be improved in an agile way. This is evidenced by new developments in fuel cell technology and the traction motors for e-mobility. For example, MAHLE is able to test its traction drives over the entire development cycle. This ranges from concept testing in pre-development in Germany, performance testing in Slovenia and China, and complete system testing of MAHLE products in the areas of electrification and thermal management on the E-axle test bench in Germany. MAHLE has been testing future topics, such as the use of hydrogen, in its own test center for several years.

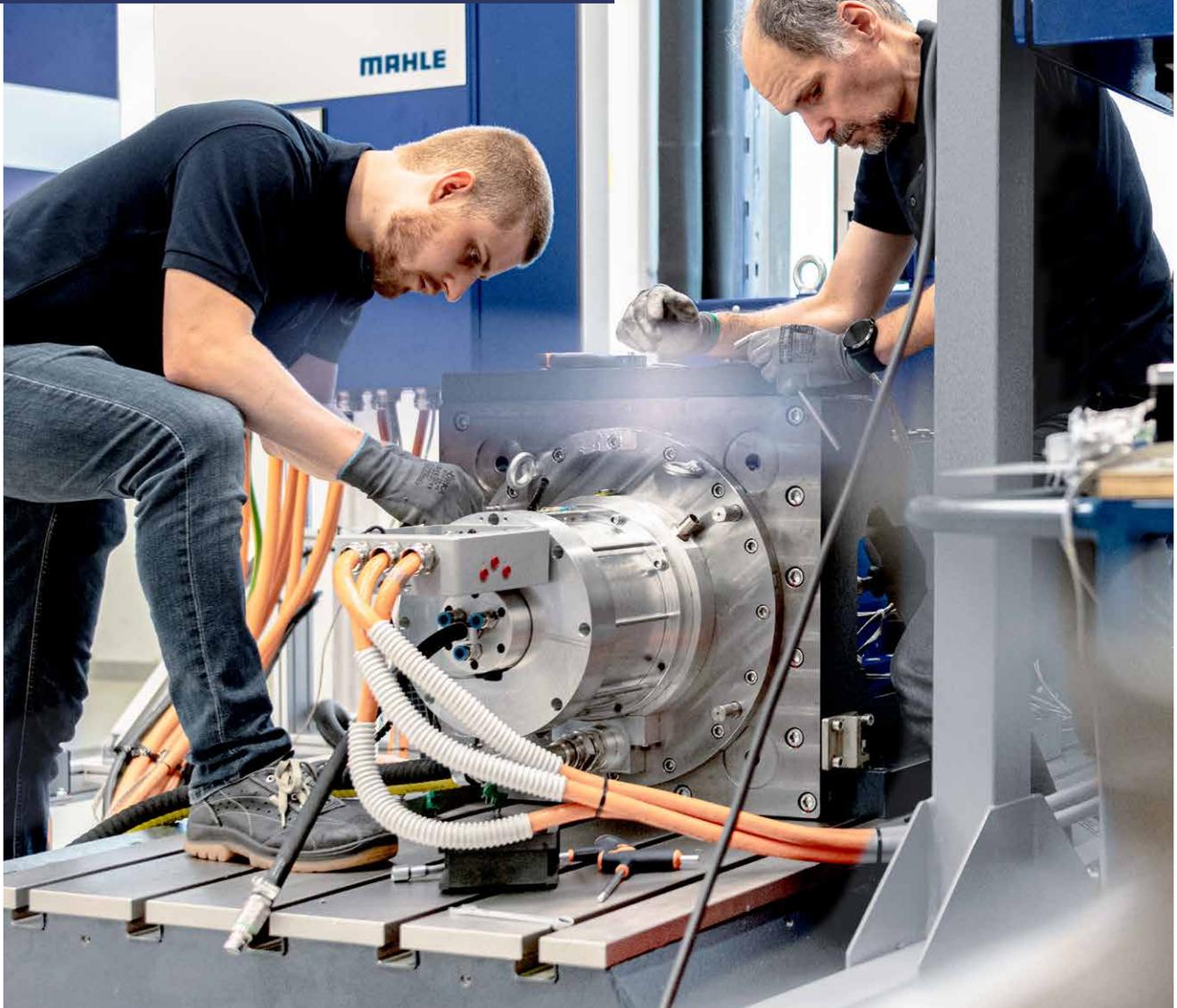




In the eastern Chinese city of **Changshu**, there is a Tech Center where future-oriented technologies, such as the e-compressor, are developed and tested. The focus here is on material analysis, performance and endurance testing, noise and vibration tests, as well as testing in climate and anechoic chambers (pictured).



The MAHLE Tech Center in **Šempeter pri Gorici**, Slovenia, is completely geared towards e-mobility and offers high-precision test benches in a range that includes the smallest electric machines through to high outputs of hundreds of kilowatts. MAHLE supports the development of new solutions for traction motors with further top-end test benches at many locations worldwide.





The H<sub>2</sub> test center in **Stuttgart**, Germany, is mainly focused on hydrogen applications. In addition to a state-of-the-art fuel cell test bench, testing is also underway with a 340 kW hydrogen engine in Stuttgart. The aim is to develop economical and robust systems solutions for the automotive industry. MAHLE is also represented in all major hydrogen engine and fuel cell development projects thanks to its development expertise.

# The street in the laboratory

*What influence does the choice of paint have on whether ice in refrigerated vans remains ice-cold? This is an important question in the supply industry, because on hot summer days the temperature on the vehicle's surface can exceed 70°C. In the climatic wind tunnel in Stuttgart / Germany, experts are trying to find the answers to this and many other questions.*

In this state-of-the-art system, all conceivable driving conditions can be precisely defined and reproduced. Additionally, a wide variety of combinations and sequences are possible with regard to temperature, humidity, wind, solar radiation, and road load. On the spacious test section, even vehicles as large as trucks can be measured under real weather conditions. In the case of the refrigerated van, the clear answer emerged after numerous simulations with various solar loads: there is a temperature difference of more than 15 K in favor of light paint compared to a dark alternative.



## For a clean future

Alternative, hydrogen-based drives and battery-electric motors will shape the future of road traffic. With its climatic wind tunnel, MAHLE is gearing up for the future, making it possible to carry out relevant tests, measurements, and simulations seamlessly.

### 100 km range in 5 minutes

The existing fast-charging station allows electric vehicles in the climatic wind tunnel to be charged with up to 350 kW DC and 915 V in all climatic conditions. The 10 m long cables easily reach every charging port. The vehicle can thus be charged or discharged in under 5 minutes for a cruising range of 100 km. The fast-charging station offers individual solutions for the wind tunnel, including control and monitoring from the control room.

### New test procedures with hydrogen

The use of hydrogen in vehicle powertrains poses new challenges for manufacturers and for the climatic wind tunnel. When using hydrogen, safety concepts must be adjusted, because even a mixture with a hydrogen concentration of just more than 4 percent by volume could be explosive. The necessary conversion measures in the MAHLE climatic wind tunnel will be completed by the end of 2025. The ultimate goal is to safely conduct the tests with future drive concepts under all climatic conditions.



## Pioneers of the measurement section

It was back in 1937 that Manfred Behr built the world's first wind tunnel in the automotive industry. And until today, MAHLE has been a pioneer in this field and has continued to develop the measurement section. Climatic wind tunnels have made realistic, precise, and repeatable measurement and testing conditions possible for diverse applications. They thus provide a reliable basis for smooth technology transfers, quality assurance, cost reduction, and time savings—all in the interests of the customers.

**Further information  
can be found here:**



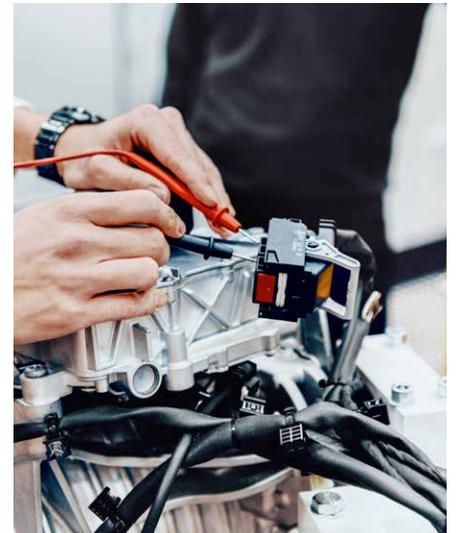
# R&D experts — MAHLE Powertrain

*The next generation of drive technology will be more varied than ever before. As an experienced specialist in powertrains of all kinds, MAHLE Powertrain supports automobile manufacturers as they take their next step forward. Engine, transmission, hybrid unit, software, and operating strategy—MAHLE Powertrain handles it all.*

If you're looking for expert engineering and consultancy services, MAHLE Powertrain is the partner for you—whatever the drive system. Its broad range of services includes the design, testing, development, calibration, and integration of hybridized internal combustion engines and electrified powertrain systems. In all projects, the ultimate goal is to achieve real innovations or advance to the next level of technology for solutions suitable for series production. As they move into the future, the experts are always there to support vehicle manufacturers as partners for cutting-edge research, development, and application.

## Battery engineering partner

With in-depth understanding of new technologies, our experts support the international automotive industry as development partners in areas such as electromobility. In the two battery development centers—one in Stuttgart and one in Northampton, England—we work on innovations for everything to do with batteries. At the same time, engineering services in this area are increasingly in demand. The newly developed M3x battery pack from MAHLE is a successful example of this within the MAHLE Group. It was designed by MAHLE Powertrain with optimised thermal management to allow high charge and discharge rates in high performance electric and hybrid vehicles.



## Advanced testing

To stay one step ahead of the latest technology trends, MAHLE Powertrain continuously invests in state-of-the-art development and test infrastructure. This is also the case at the e-drive test center in Fellbach near Stuttgart/Germany, where the team is developing and testing e-axes and e-drive units for a wide range of electric and hybrid vehicles. To ensure compatibility with all potential vehicle drive applications, systems are operated with high-voltage and low-voltage batteries. Highly specialized permanent-magnet synchronous electric motors replicate the loads applied by the driven wheels, while a thermal soaking system makes it possible to test e-drives in a wide temperature range.



### International presence

As the MAHLE Group's Engineering Services subsidiary, MAHLE Powertrain supports customers independently of the parent company in the selection of the most appropriate technologies or components for specific requirements. MAHLE Powertrain is represented internationally with eight locations in the UK, Germany, the USA, and China. This means that customers in the world's major automotive markets can work directly with MAHLE experts on site.



## SUSTAINABILITY

# Sustainability at MAHLE

*For MAHLE, sustainability means creating a future in which environmental protection, safety at the workplace, good corporate governance, and economic efficiency go hand in hand. The guiding principles here are ethically correct and legally compliant behavior, protection of the environment and resources, and the well-being of the company's employees.*

MAHLE is a leading international development partner and supplier to the automotive industry, with customers in the passenger car and commercial vehicle sectors. The technology company is working on the climate-neutral mobility of tomorrow. Its focus is on e-mobility, thermal management, and other technologies to reduce carbon emissions, including fuel cells or highly efficient, clean combustion engines that also run on renewable fuels, such as hydrogen.

From engine systems and components to filtration and thermal management, the product portfolio covers all relevant technical aspects of drive and air conditioning technology, as well as the combination of these elements. With a high level of systems expertise and many years of expert knowledge in electrical and electronic components and systems, MAHLE also offers integrated systems solutions for e-mobility. All MAHLE components and systems have been used off road for decades—in steady-state applications as well as in mobile machines, railroad traffic, and shipping.



Comprehensive information about our sustainability activities can be found in the current Sustainability Report:



[mahle.com/en/news-and-press/publications](https://mahle.com/en/news-and-press/publications)

# 145

In 2023, energy efficiency projects resulted in energy savings of about 32 GWh.

# 372 GWh

of renewable electricity was generated in 2023, an increase of 10 percent on the previous year.

## Even cleaner

It will still take time before e-mobility becomes established worldwide. The combustion engine will likely continue to play an important role for decades in some markets and for certain application scenarios. That is why MAHLE continues to work on optimizing established technologies. The goal is to make the internal combustion engine even cleaner and more efficient, therefore consuming less energy and producing lower emissions.

The company aims to have carbon-neutral production at all its locations worldwide by 2040. MAHLE has drawn up an ambitious roadmap for this. This includes, among other things, increasing its own electricity production.

To this end, MAHLE commissioned another photovoltaic system for its plant in Izmir, Turkey, in 2023. The goal for MAHLE is to reduce emissions, while at the same time promoting independence from the volatile energy market.

In addition, individual locations are to increase their energy efficiency by at least two percent per year. The company is looking to set its balance sheet to zero by purchasing carbon-neutral-generated electricity and compensating remaining emissions.

“

Our CO<sub>2</sub> roadmap is an essential element of our MAHLE strategy. We have set ourselves company-wide reduction targets and are working to achieve carbon-neutral production by 2040.

**Georg Dietz**

Member of the Management Board,  
responsible for sustainability at MAHLE



# Green milestones

In 2023, MAHLE reached important milestones with its climate protection measures: CO<sub>2</sub> emissions from the use of fossil fuels (Scope 1) and emissions from the use of purchased electricity (Scope 2) could be reduced by 43 percent in comparison with the base year 2019. In addition, MAHLE expanded its objectives for Scope 3, i.e. emissions along the supply chain.

By 2030, the technology group wants to reduce greenhouse gases in this area by 28% compared to 2019. To underline the commitment to achieving the goals of the Paris Climate Agreement, MAHLE has had its Scope 1–3 targets for 2030 externally validated by the Science Based Targets initiative (SBTi). The SBTi has recognized the climate targets according to scientific criteria.



## Scope 1 & 2

Emissions caused by the company itself and consumption of purchased electricity and heat



## Scope 3

Greenhouse gas emissions along the supply chains and product use



**2021**

MAHLE in Germany  
CO<sub>2</sub>-neutral



**2030**

MAHLE worldwide  
-49% CO<sub>2</sub>\*



**2040**

MAHLE worldwide  
CO<sub>2</sub>-neutral



**2030**

MAHLE worldwide  
-28% CO<sub>2</sub>\*

2020

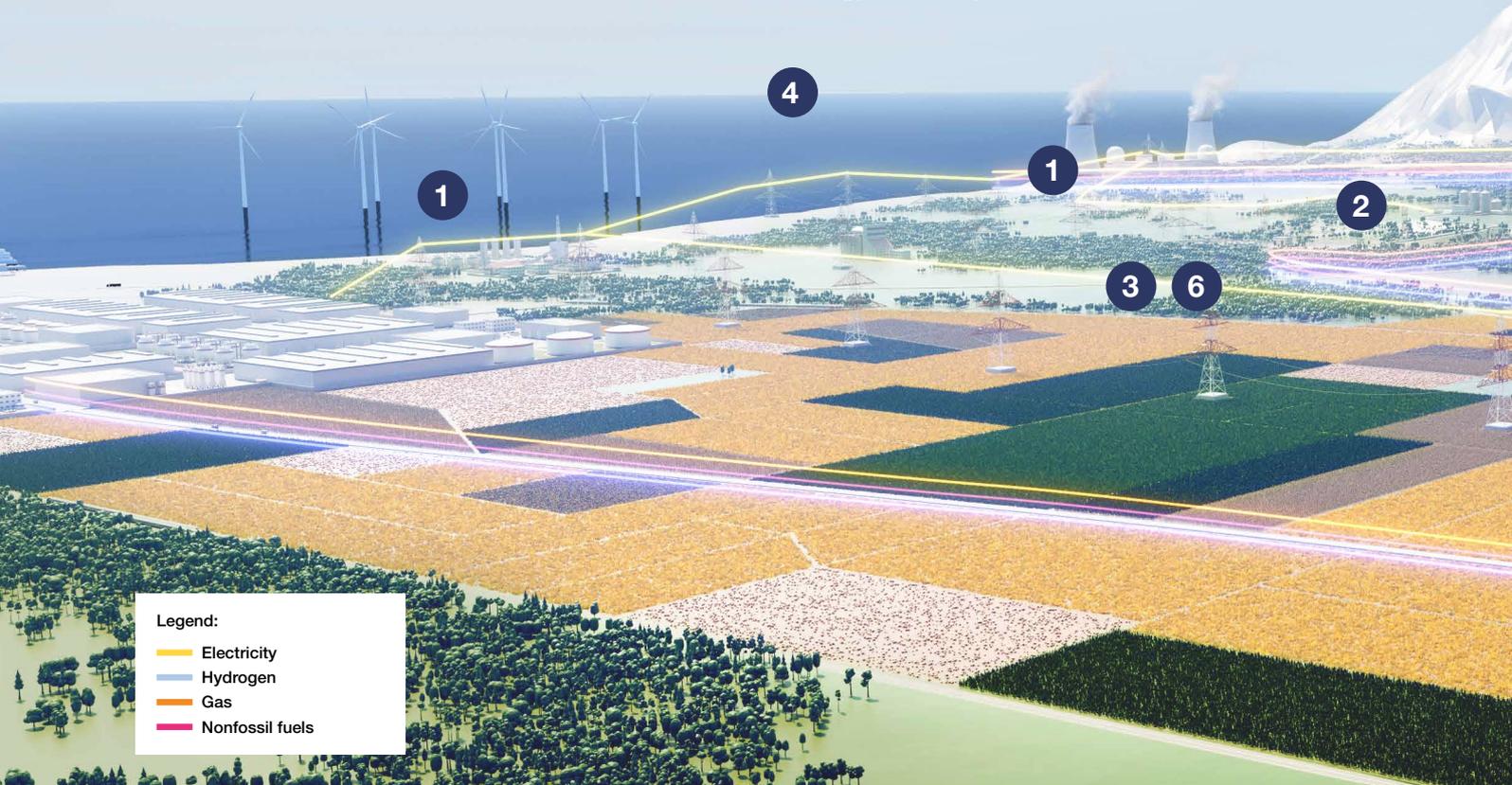
2030

2040

\* In relation to 2019

# Zero-Carbon Road Map

*The fossil fuel phaseout in the transportation sector brings with it profound changes. What will be the energy carriers of the future for road, rail, and water? Which resources will be used? A look at tomorrow's energy landscape.*



## 1 A variety of sources:

Wind, solar, hydropower, biomass, and natural gas with carbon capture—many low-carbon energy sources will play a key role in the energy mix of the future.

## 2 Conversion:

Many forms of energy and raw materials cannot be used directly, but must first undergo conversion. Here are two examples: surplus electrical energy from renewable sources can be converted into hydrogen via electrolysis, and biomass can be converted into biogas.

## 3 Grid and storage:

Energy is often produced centrally in large plants and transported from there via pipeline to a wide range of users. Chemical energy carriers, such as hydrogen and e-fuels, can also be used as a storage medium. When it comes to electricity, the power grid acts exclusively as a means of transmission.

## 4 On land:

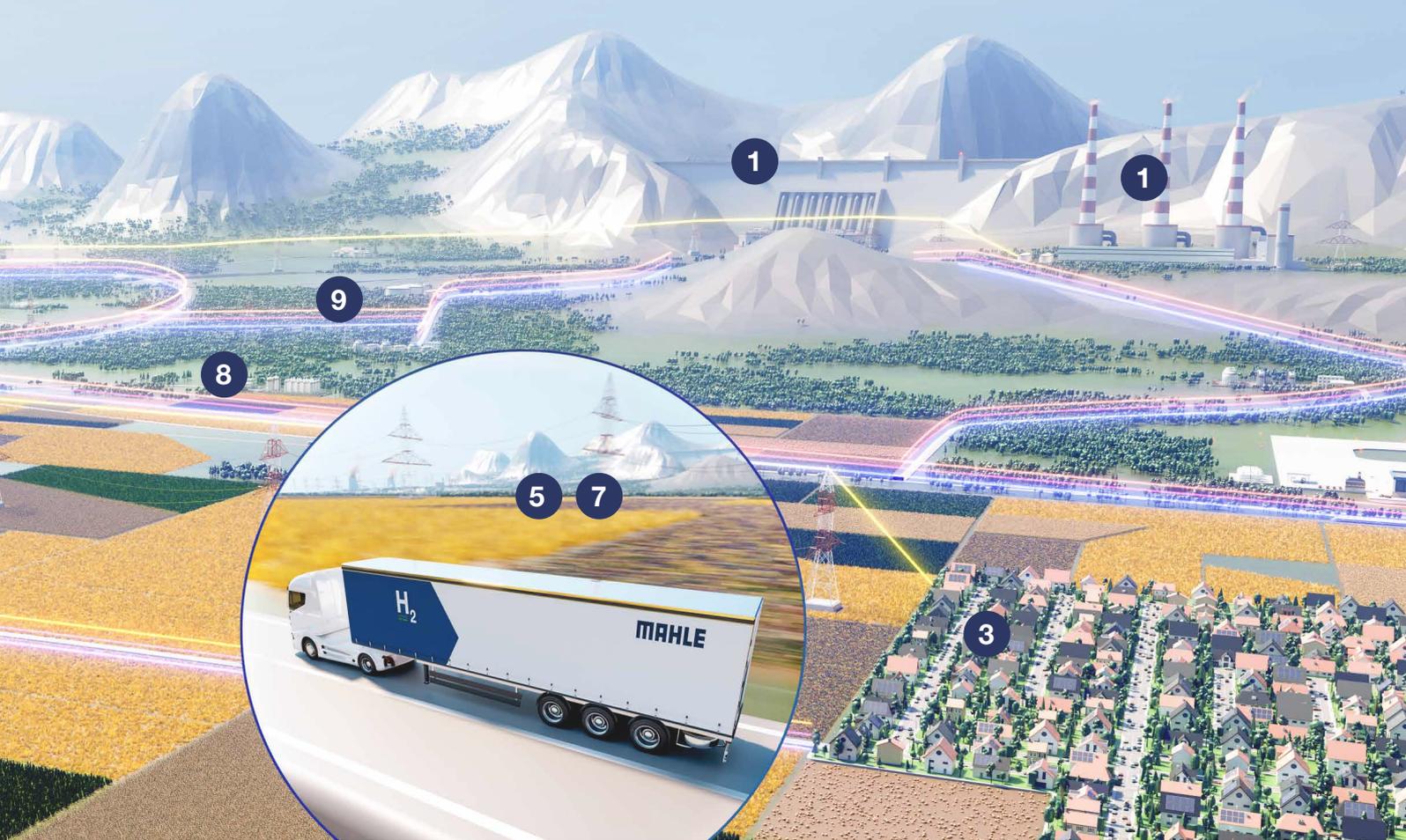
In the defossilized transportation sector on land, all forms of energy—electricity, hydrogen, e-fuels/biofuels, and biogas—will play an important role in the medium term. Among other things, the daily mileage defines the different use cases.

## 5 On water and in the air:

There are limited refueling possibilities in shipping and aviation. Additionally, aircraft turbines and marine engines need fuel with a high energy density. Synthetic fuels and e-fuels are therefore the most likely solution, especially for long distances.

## 6 Electricity:

Carbon-neutral electricity is the key to achieving climate neutrality. It can be obtained from solar energy, biomass, or wind energy. However, to keep the grid stable, supply and demand must be balanced,



or the electricity must be temporarily stored in hydrogen by means of electrolysis, for example. In the mobility sector, the direct use of electricity in battery electric drives is especially suited to lighter vehicles and shorter distances.

### 7 Hydrogen:

Hydrogen will be a key component of the future energy mix. In the mobility sector, it can be used directly in fuel cells and internal combustion engines. Thanks to its high energy density, it is an excellent choice, especially for long-haul transportation. In industrial sectors, such as steel or chemicals, hydrogen has great potential to help reduce CO<sub>2</sub> emissions. It can also be used to store electricity from volatile renewable energy sources or as a feedstock for synthetic fuels.

### 8 E-fuels/biofuels:

Biofuels and e-fuels produced using renewable energies offer a promising opportunity to use both the current infrastructure and the current vehicle fleet to reduce CO<sub>2</sub> emissions right away through their use as admixtures, for example.

### 9 Gas:

Gas produced from biomass can be fed into the existing gas and storage network and then used in a range of applications, for example, to operate buildings or large marine engines. In addition, its use in gas-fired power plants to generate electricity contributes to stabilizing the power grid and reducing the consumption of gas. In addition, CO<sub>2</sub> generated during production can be separated off in a technical process at the power plant and stored underground.

## RAILWAY VEHICLES

# Reliable mobility on the railway track



*Steadily growing flows of goods and increasing mobility result in ever higher demand for performance and efficiency in railway transportation. Complex vehicle architectures and extreme operating conditions pose new challenges for the products and components. MAHLE supplies reliable, durable, and performant vehicle components and systems for a troublefree operation.*

MAHLE is constantly setting new standards when it comes to cooling diesel-driven and electrically powered railway vehicles. As a systems partner, it also understands the complex requirement profiles and different operating conditions on the railway track.

**Excellent reliability**

Cooling Systems for high-speed trains that travel at up to 550 km/h offer high cooling performance with minimum weight and low operational energy consumption.

**Compact cooling**

Space-optimized Cooling Systems for multisystem locomotives (up to 6,500 kW) and modern combustion engines (up to 3,500 kW) can be operated at altitudes of up to 5,000 m and at ambient temperatures ranging from +50 °C to –50 °C.

**Sophisticated systems**

Complete Locomotive Construction Segments are equipped with Coolant Components, Hydraulic Drive Equipment for Blowers, Compressors, and/or Auxiliary Generators.

*In railway traffic, too, alternative drives and the further optimization of advanced combustion engines are the key to reducing emissions. With its cooling systems for all drive types, MAHLE is a strong development partner for the sustainable mobility of the future.*

## Dual-mode & last-mile cooling modules

The combination of catenary powered traction and low-emission combustion engines in one vehicle requires intelligent and compact solutions. MAHLE provides cooling modules for numerous dual-power vehicles and electric locomotives with auxiliary diesel power units in mainline and shunting operations.



## Battery and hybrid drives

Efficient thermal management keeps batteries and power electronics within the optimum temperature range, thereby extending the service life of these components. MAHLE Cooling Systems thus enable the use of powerful battery and hybrid drives.



## Fuel cell drive

High thermal loads are generated in modern fuel cell trains. The coolant temperature and cooling circuit conductivity must be kept low for reliable operation. MAHLE Cooling Systems are made from high-grade materials and have a high cooling density. Selected as a partner for various hydrogen test vehicles, MAHLE supports its customers with its know-how right from the start.



## INDUSTRIAL APPLICATIONS

# Peak performance for drives and the environment

*In industry—whether ships, commercial vehicles, or trains—thermal management is essential when it comes to demanding industrial applications and special vehicles. Doing so not only reduces fuel consumption, but also cuts emissions and optimizes performance.*

In addition to an extensive standard range, MAHLE offers cooling concepts for specific applications in various materials:

## Disk-type Charge Air Coolers (CounterFlow [CF] Charge Air Coolers)

- Charge air and coolant flow in opposite directions
- Made from aluminum and stainless steel
- Up to 70 percent lighter and 50 percent smaller than conventional coolers
- No heat protection is required on the component thanks to the circulating coolant flow



## Charge Air Coolers in aluminum package design and fin & tube design

- Maximum flexibility to scale in size
- High power density combined with low weight
- Very good compressive strength and vibration resistance
- Long service life even at temperatures exceeding 250 °C



## Charge Air and Gas Mixture Coolers in nonferrous metal round-tube design

- Highly resistant to extreme stress
- Seawater or poorly maintained coolant may be used as cooling medium
- Can be used for natural gas, biogas, landfill gas, and special gas applications
- Choice of application-specific materials
- Mechanically joined (with no soldering process)





High-quality and durable components are indispensable for the reliable, safe, and environmentally friendly operation of industrial applications.

#### Exhaust Gas Coolers

- As tube bundles for engines up to 560 kW
- With round tube and fin for engines above 560 kW
- Made of high-grade stainless steel



#### Battery Thermal Management Systems

- Stabilization of the battery temperature in electronic applications
- Energy-efficient operation for maximum cruising ranges



#### Oil and Fuel Coolers

- Cooling by Stacked-plate Coolers at high thermal loads
- Can be mounted on the drive without additional housing
- Vacuum-brazed oil coolers, available in aluminum or steel/stainless steel
- Resistant to pressure and vibration
- Media counterflow (oil/coolant, oil/oil, and fuel/oil coolers)



## INDUSTRIAL APPLICATIONS

# Large engine components



*The development and production of premium engine components has always been a core competence of MAHLE. In the large-bore piston segment, the company has successfully established itself as the market leader. Pistons, piston pins, and cylinder liners from MAHLE are the driving force behind the powerful engines used in shipping, construction, industry, power generation, and rail transportation. The engine components are also used worldwide in engines that run on alternative and CO<sub>2</sub>-neutral fuels such as hydrogen.*

## Power cell units

The power cell unit (PCU) consists of the piston, piston pin, piston rings, and cylinder liner. Power cell units are developed as complete modules. They offer particularly high functionality and efficiency because the individual components are optimally coordinated. This saves time and costs—especially during the development phase. Nonetheless, all individual components can be tailored to the respective requirements. We consequently offer our customers maximum flexibility with the advantages of an integrated overall system.



# Pistons

As the largest piston manufacturer worldwide, our portfolio includes a variety of product and material choices: cast or electron beam-welded aluminum pistons, as well as composite pistons with aluminum, nodular cast iron, and steel skirts. The MAHLE piston range for large engines includes products with diameters of up to 580 millimeters.

## Composite pistons

### Steel-aluminum pistons

Composite pistons with a crown made of forged steel and a forged aluminum alloy skirt have established themselves over the whole diameter range from 150 to 580 mm. The pistons are suitable for low to medium peak cylinder pressures and are nowadays one of the standard piston design in medium speed engines.



### Steel-NCI pistons

The composite piston design with a forged steel crown and a nodular cast iron skirt is used for peak cylinder pressures exceeding the limits for aluminum alloy skirts. Key features include low cold piston clearance and the resulting low secondary piston motion as well as high seizure resistance. With an appropriate design, it is suitable for peak cylinder pressures higher than 20 MPa. Compared with pistons with aluminum skirts, however, there is a mass increase due to the higher material density.



## Steel-steel pistons

Steel pistons meet the expectations for high end, highly loaded, and special applications. They provide ultrahigh component strength and an extended lifetime.



## Monobloc pistons

### Aluminum pistons

Aluminum pistons nowadays are typically designed for diameters up to 260 mm. The low weight of the piston and the high variety of bowl geometries are just two big advantages of the design. Ring carriers for reducing the wear of the first ring groove as well as a saltcore cooling gallery for a better cooling of the ring land and the bowl rim can easily be implemented. Electron beam-welded aluminum pistons can be used for higher peak cylinder pressures. This piston design combines the advantages of a forged piston skirt with the benefits of cast ring bands.



### Steel pistons

Steel pistons are also available as friction-welded (MONO-WELD®) or high-temperature brazed (HTB®) versions with a forged steel crown and skirt.



CONSTRUCTION &amp; AGRICULTURAL MACHINES

# Robust all-rounders



*Cold starts, high pulling, hydraulic and lifting power over a long period of time, precise maneuvering in even the most confined spaces, and high torque at low speeds—the engines and transmissions found in agricultural and construction machinery have to function reliably at all times.*

The safety of the operators of these machines also has to be ensured. They must often contend with intense heat, dry cold, high humidity, or grain and road dust. Cooling and air conditioning systems, starter motors and alternators, and filtration systems from MAHLE get the job done on fields and construction sites around the world. The lightweight components and systems operate highly efficiently and can be tailored to customer requirements.

### Battery Cooling System

- Roof or chassis mounted
- Passive cooling for moderate ambient temperatures by means of a radiator
- Active cooling for higher ambient temperatures by means of a cooling unit
- Standardized variants and customized developments possible
- Stepless heating via electric high-voltage heater
- Cooling performance up to 14 kW
- Heating performance up to 20 kW
- 24 V supply voltage
- CAN bus control interface
- High-voltage connection with integrated distribution box



### Heat Pump

- Thermal management of electric vehicles, especially for heating and cooling cabins and batteries
- Dimensions: 330 mm × 430 mm × 340 mm, weight: 16 kg
- Heating performance of up to 14 kW, cooling performance of up to 11 kW
- R1234yf or R134a refrigerant
- 800 VDC nominal current supply (full performance range 450–860 V)
- Control interface (for compressor and expansion valve) LIN 2.1



### Modular Heat Exchanger Platform (tube & fin)

- Standardized systems for radiators, charge air coolers, oil coolers, and lightweight, high-performance, and durable condensers
- Modular concept with tubes of various lengths as well as a flexible number of tubes in depth and width
- Broad output range for various applications (ICE, FC, BEV)
- Automotive technology adapted to the specific requirements of agricultural and construction machinery
  - Corrugated fins to avoid contamination and for steam cleaning
  - Increased vibration resistance and durability
  - High power density due to optimized fin geometry





## INDUSTRIAL VEHICLES

# Future-oriented logistics

To safely transport materials and goods—whether textiles, food, or raw materials—you need powerful vehicles such as pallet trucks, tractors, and forklifts. By keeping the flow of goods and materials moving, these constitute an essential part of logistics, industry, and trade. MAHLE offers safe and efficient solutions for complex loading and unloading operations involving heavy loads.

### Individual complete systems

Electric drives for industrial vehicles are not only more environmentally friendly, but also wholly suited to use in enclosed spaces. MAHLE offers drive systems for electric forklifts such as pallet trucks (24/36 V) and three- and four-wheel counterbalance trucks (48/72/80 V). Different electric motors can be combined with the corresponding control units. Thanks to their modular design, the complete systems meet the specific requirements of each field of application, whether as traction systems, for power steering, for hydraulic pumps, and so on.

### The right functions for each application

- High performance and precise steering when carrying heavy loads thanks to double drive system
- Excellent maneuverability and stability due to coordination of the drive and steering controllers via the CAN unit
- Multifunctional master/combined control system
- Support for peripherals through digital and analog I/O modules
- Protection of all components against thermal and other influences
- All components compliant with European CE standards as well as American UL standards and compatible with automotive EMC standards
- Possibility of integrating accessories into the system, such as steering units, drawbar boxes, CAN units, and graphic displays

# Products

## AC Induction Motors for the traction system

- Nominal voltage: 15–50 V<sub>AC</sub>
- Nominal power: 4–18 kW



## IPM Motors for the traction system

- Nominal voltage: 15–50 V<sub>AC</sub>
- Nominal power: 4–10 kW



## AC Systems for the steering system

- Nominal voltage: 24–48 V<sub>AC</sub>
- Nominal power: 0.15–0.9 kW



## AC Induction Motors for the hydraulic system

- Nominal voltage: 15–50 V<sub>AC</sub>
- Nominal power: 3–28 kW



## DC Motors for the hydraulic system

- Nominal voltage: 24–48 V<sub>DC</sub>
- Nominal power: 1.4–2.2 kW



## AC Electronic Control Unit for the hydraulic system

- Nominal voltage: 24–80 V
- Max. phase current: up to 240 A
- Power supply outputs: 5 and 12 V
- Sensorless controller available



## AC Electronic Control Unit for the traction system

- Nominal voltage: 24–80 V
- Max. phase current: up to 450 A
- Power supply outputs: 5 and 12 V



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