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Reboost

A comprehensive view on the changing powertrain component market and how suppliers can succeed

Unless explicitly stated otherwise, the powertrain revenue figures in this publication are generated by the McKinsey Powertrain Revenue Model (“Reboost!”), which draws upon expert interviews, research from the McKinsey Center for Future Mobility, and vehicle-volume data from the IHS Markit Alternative Propulsion Forecast of August 31, 2019. The powertrain revenue outlook based on our proprietary model, however, is neither associated with nor endorsed by IHS Markit.

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A comprehensive view on the changing powertrain component market and how suppliers can succeed

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Content

Introduction and key messages

Looking back not even a decade, the automotive industry was largely comprised of the same two powertrain types that had characterized the industry for over a century: gasoline and diesel. Today, there is a broad powertrain mix as the industry – prompted mostly by government mandates – pushes towards more environmentally friendly and efficient transportation. As the powertrain portfolio diversifies and includes an increasing number of hybrid and electric varieties, the powertrain component landscape is becoming more complex and dynamic.

Due to these developments that are both driven by and affecting OEMs, suppliers, and new entrants alike, which are taking place at a pace that not many would have foreseen a few years ago, a comprehensive view on the changing powertrain component market is needed. Based on extensive proprietary research and analyses (Text box 1), this report aims to provide a perspective on three questions that are a top priority for all sector players and especially for suppliers:

1. Why, to what extent, where, and by when will there be significant changes in the powertrain market?

2. What are the most important changes in the powertrain market regarding its main components and systems?

3. How will the changes impact the current powertrain value chains and how can suppliers successfully respond?

Text box 1: How we derived insights for this report

Based on the overall vehicle production growth as well as the shift in powertrain mix, we built a detailed, bottom-up model simulating the market development of 28 powertrain component markets. The simulation is based on the evolution of unit sales combined with average industry prices for the powertrain component and subsystems.

Our model projects revenue for the component market, broken down by region, vehicle segment, and powertrain type over a 2018 to 2025 time frame. The model can be also used to conduct scenario-based component market simulations beyond 2025.

We first seek to describe the full set of powertrain technologies, identify their strengths and weaknesses, and assess the impact of various forces on their development and adoption trajectories. We then forecast the growth and understand the structural dynamics of the global powertrain market via a detailed, component-by-component analysis of the various trends – presented in the context of four ICE component categories, three high-voltage (HV) electrification categories, and one fuel cell category.

By projecting the shifts in the powertrain component market and understanding how they will likely impact suppliers, we have derived four key messages:

— E-mobility is at a tipping point. Stronger CO_2 regulations, consumer preferences increasingly leaning towards clean transport solutions, declining battery costs, and infrastructure rollout acceleration will lead to faster distribution of electric vehicles (EVs)[1] throughout major markets in the early 2020s.

— The mix of powertrain technologies underlies several forces and will vary by region. Regulation, technology, infrastructure, total cost of ownership (TCO), and consumer preferences will be the drivers of the speed of adoption of alternative powertrains over the next five to ten years. These forces vary strongly by region and so will the mix of EVs, hybrid vehicles, and later, fuel cell electric vehicles.

— Powertrain content will see dramatic change. The diversity of powertrain types is leading to a significant change in the powertrain content per vehicle over time – in quantity, technology, and share of vehicle value. Suppliers need to understand these changes to be able to identify relevant pockets of growth (in electrification) and stagnating or declining component markets (in ICE).

— Suppliers are refining their strategies in response to a shifting component market. Many suppliers are taking a careful look at their existing competencies, the markets they are active in, their long-standing customer relationships, new mobility players, as well as individual ambitions to reshape their portfolio strategies.

In order to help suppliers to successfully navigate the powertrain transition, we offer a four-step approach that can guide them regardless of their starting points, aspirations, or player-specific value pools.

Each of these statements will be explained in more detail in the following chapters.

1 Throughout the text, EV refers to battery electric vehicles (BEV) and plug-in electric vehicles (PHEV).

1 Perspective on the automotive powertrain market

1.1 Entering the portfolio game – a technology-neutral assessment of different powertrain architectures

A broad mix of powertrain technologies is currently evolving as the industry – mostly prompted by government mandates – pushes towards more environmentally friendly and efficient transportation (Text box 2).

Text box 2: Overview of today's automotive powertrain landscape

We have defined seven types of powertrains currently on the market. Here is a brief overview of their technologies and applications and an assessment of how they stack up against key environmental, performance, and economics dimensions:

The internal combustion engine (ICE), both gasoline and diesel, is the dominant powertrain. Through downsizing, turbocharging, and aftertreatment of the systems' tailpipe, emissions have decreased substantially over the last decades and will continue to do so.

Mild hybrids (MHEVs) are the entry point to electric powertrain technologies. A low-voltage (LV) system (mostly 48V) enables the use of efficient electrification elements, such as start-stop, regenerative braking, and some level of power assist the ICE. MHEVs usually do not have an exclusive electric-only mode of propulsion.

Hybrid electric vehicles (HEVs) are designed to optimize the use of the combustion engine in interplay with a small, low-range, HV electric powertrain, e.g., for low-speed cruising or power boost.

Plug-in hybrid electric vehicles (PHEVs) have a similar architecture to HEVs, yet they have a significantly larger battery, a more powerful electric engine, and can be recharged by plugging into an external source of power. They are designed for a significant share of pure electric driving with a typical range of 30 to 60 kilometers today and possibly 60 to 80 kilometers in the near future.

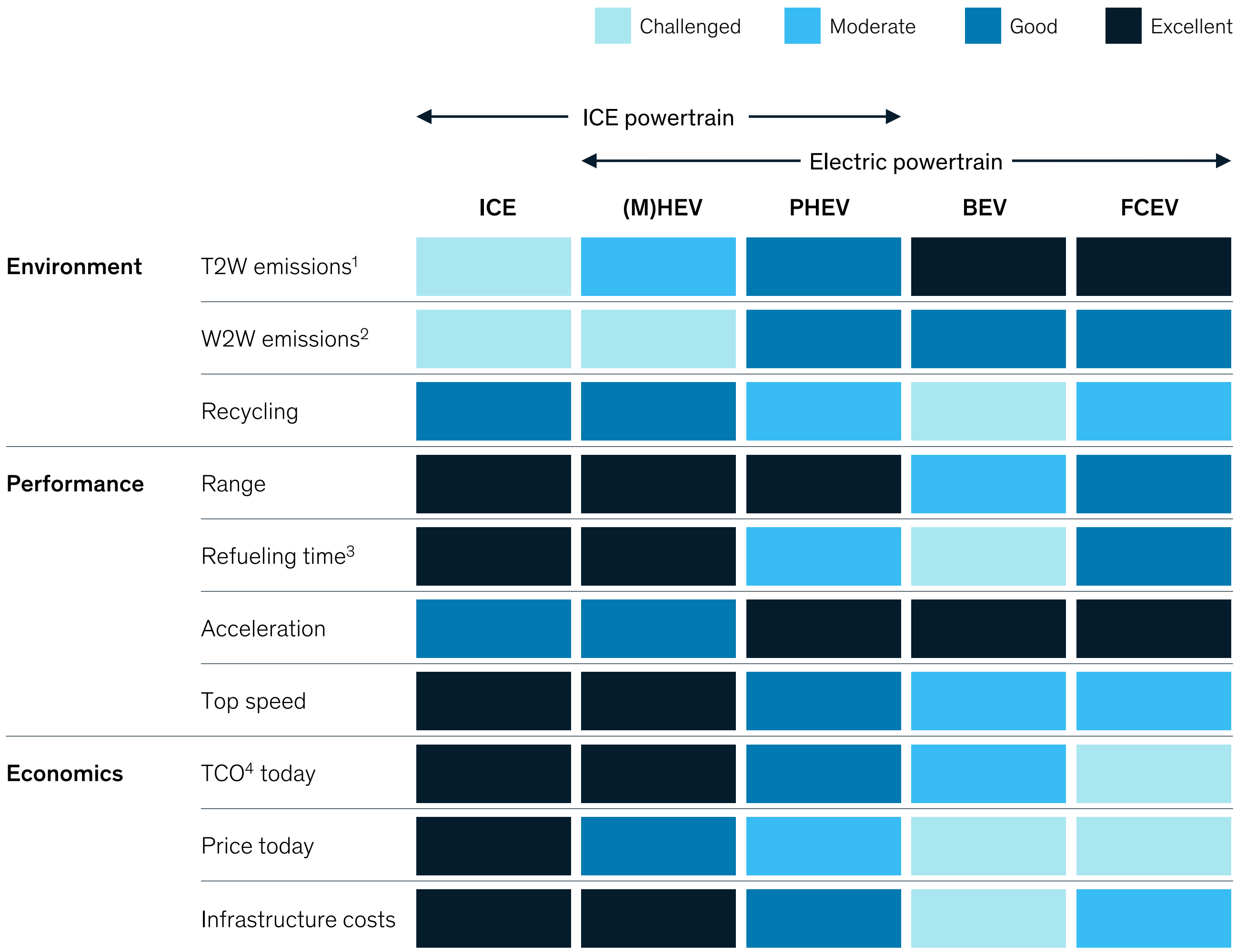
Battery electric vehicles (BEVs) replace the combustion engine with an electric engine. As battery costs continue to decline, BEVs will eventually offer lower total cost of ownership (TCO) to customers than ICE or hybrid vehicles. A dense network of charging infrastructure is required to enable a large penetration of EVs over the next decade.

Fuel cell electric vehicles (FCEVs) fundamentally function like BEVs but store energy as a pressured hydrogen gas and produce electricity from that energy with a fuel cell. The energy density of storing hydrogen is, both by volume and weight, significantly higher than in batteries, which means vehicles can carry more energy. In addition, fueling speed can be in the order of a few minutes. This makes them well suited to applications with high power and long-distance requirements, e.g., trucks and commercial vehicles.

However, as there is no single winning powertrain technology today, the diversity and complexity of the powertrain value chain is creating a profound disruption for vehicle manufacturers and suppliers alike (Exhibit 1). Traditional tier-1 and tier-2 suppliers, new suppliers from outside automotive, and start-ups are entering the e-powertrain market and competing for dominance in the next era of powertrain technology. This puts pressure on individual players and affects both current and future profit pools in the powertrain industry.

Exhibit 1

Strengths and limitations of today's powertrain technologies



Key characteristics, indicative		ICE	(M)HEV	PHEV	BEV	FCEV
	ICE power, kW	50-400	50-400	50-200	–	–
	Electric power, kW	–	<25	<100	>100	>100
	Battery capacity, kWh	–	<2	<30	>40	<10
	T2W CO_2 savings, % CO_2	–	10-20	50-80[5]	100	100

1 Tank-to-wheel emissions, i.e., tailpipe emissions that a vehicle produces locally via the combustion of fossil fuels; these emissions are subject to current regulations globally
2 Well-to-wheel emissions, i.e., emissions related to the fuel cycle or generation of electricity, the production of the vehicle and battery, and the use of the vehicle; largely dependent on a country's energy mix
3 Considering only the time needed to refuel/charge the vehicle, not infrastructure availability
4 Total cost of ownership, strongly depending on region and vehicle segment
5 Estimated CO_2 savings considered for certification tests

Source: McKinsey Center for Future Mobility

1.2 Electrification scenarios – various forces that determine the speed of adoption

Over the next decade, four key factors will determine the speed of adoption of alternative powertrains. In addition, the penetration of EVs and HEVs, and later FCEVs, will vary strongly by region.

Regulation

CO_2 regulations in all major regions but the US are becoming more rigorous, thereby accelerating the shift from ICEs to EVs. Europe is leading the way with an emission limit of 95 g/km by 2020 and further reduction of 37.5 percent by 2030, resulting in a limit of 59 g/km. To meet the CO_2 target in Europe and avoid penalties, OEMs will have to sell 2.2 million EVs (assuming 50 percent PHEVs and 50 percent BEVs) in 2021. In 2018, EV sales in Europe amounted to 0.2 million. In comparison, China's regulation targets are set at 117 g/km and 93 g/km, and North America's current targets are set at over 50 mpg following passenger-vehicle Corporate Average Fuel Economy (CAFE) standards (equivalent to 99 g/km) for 2025.[1] In addition, further emission regulations (e.g., nitrogen oxides (NOx), particulates), access regulations (e.g., local diesel bans, license plate regulations), and potential ICE bans will influence adoption on a regional and city level. Globally, several countries have announced targeted end dates for ICEs (e.g., Norway by 2025; Israel, India, and Denmark by 2030; Canada, the UK, and China by 2040).

Infrastructure

We estimate a cumulative investment of approximately USD 50 billion will be needed in charging infrastructure by 2030, not including necessary grid upgrades. (The number of public and private charging stations needed by 2030 would be 15 million in Europe, 14 million in China, and 13 million in North America)[2]. Public grid upgrade will be a key enabler for driving EV adoption rates in China and Europe, while we project about 50 to 70 percent of the charging in North America to be taking place at home. This is confirmed by the fact that range and the ability to charge a vehicle remain the strongest concerns in Europe and the US, and the second strongest in China.[3] While it is difficult to forecast actual buildout rates, the currently strong investment momentum in China and Europe (supported by public subsidies) and awareness are cause for optimism that insufficient EV infrastructure may only be a bottleneck for a few markets (resulting in a "chicken-egg problem").

In addition to the charging station buildout, grid operators will have to respond to locally increasing peak loads (e.g., in residential areas with many early adopters) by upgrading transformers or incentivizing consumers to shift charging load (smart charging).

Technology

Innovation in battery technology and production have made EVs competitive with conventional combustion engine vehicles. Batteries constitute a major cost item in BEVs, and their cost has decreased significantly thanks to technology advancement, production process optimization, and economies of scale. Since 2010, the cost in USD/kWh has dropped by approximately 85 percent, thereby opening the market for EVs further. In 2019, battery pack costs came down to approximately USD 178/kWh on average and USD 157/kWh for best in class. Accordingly, cell costs were at approximately USD 134/kWh on average and USD 115/kWh for best in class. A further cost reduction down to USD 100/kWh is expected as chemistries are optimized and large battery factories begin producing at high yield and full utilization. With cell prices expected to reach a USD 100/kWh price level over the next five to seven years, C/D segment vehicles will reach TCO parity (depending on the annual mileage), thus enabling mass market penetration of EVs. Besides the cost of an EV, regional differences in subsidies, electricity versus fuel prices, taxes, and resale values will lead to different customer adoption rates across regions.

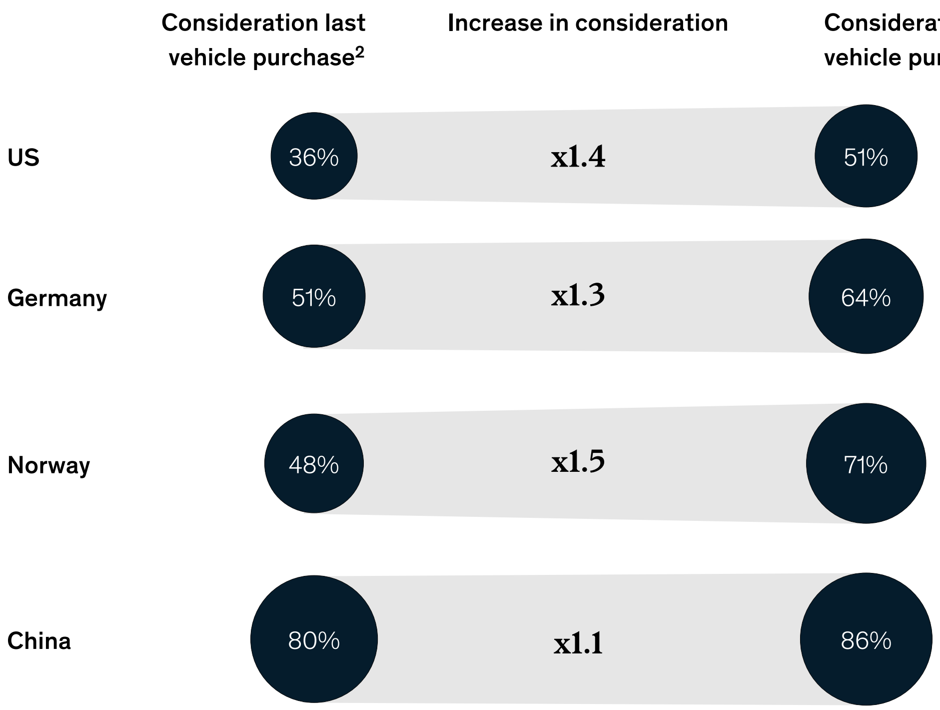
1 In the US, currently proposed national SAFE standards would reduce and freeze standards for passenger vehicles from 2021 onwards with the collective target for light trucks and passenger cars of 37 mpg in 2025.
2 Charging ahead: Electric-vehicle infrastructure demand, McKinsey, October 2018
3 McKinsey EV consumer insights 2019

Consumer preferences

With regulatory forces, technology improvements, and infrastructure rollout all in favor of EVs, the question remains, how likely are consumers to adopt? Based on a preview of our proprietary McKinsey Global Electric Vehicle Survey, we anticipate an increase in EV purchase consideration by consumers across core markets (Exhibit 2). More than 50 percent of approximately 10,000 customers asked in the US, Germany, Norway, and China responded that they are considering the purchase of an EV as their next vehicle, up to 1.5 times more than during the last purchase. The McKinsey Center for Future Mobility will publish a report on EV consumer insights in Q4 2019, analyzing the underlying consumer preferences and concerns.

Exhibit 2

Level of consumer consideration to buy an EV[1]



1 PHEV and BEV
2 Last purchase – US: 19 months ago, Germany: 21 months ago, Norway: 22 months ago, China: 18 months ago
3 Next purchase expected – US: 19 months, Germany: 22 months, Norway: 25 months, China: 16 months

Source: McKinsey EV Consumer Survey 2019

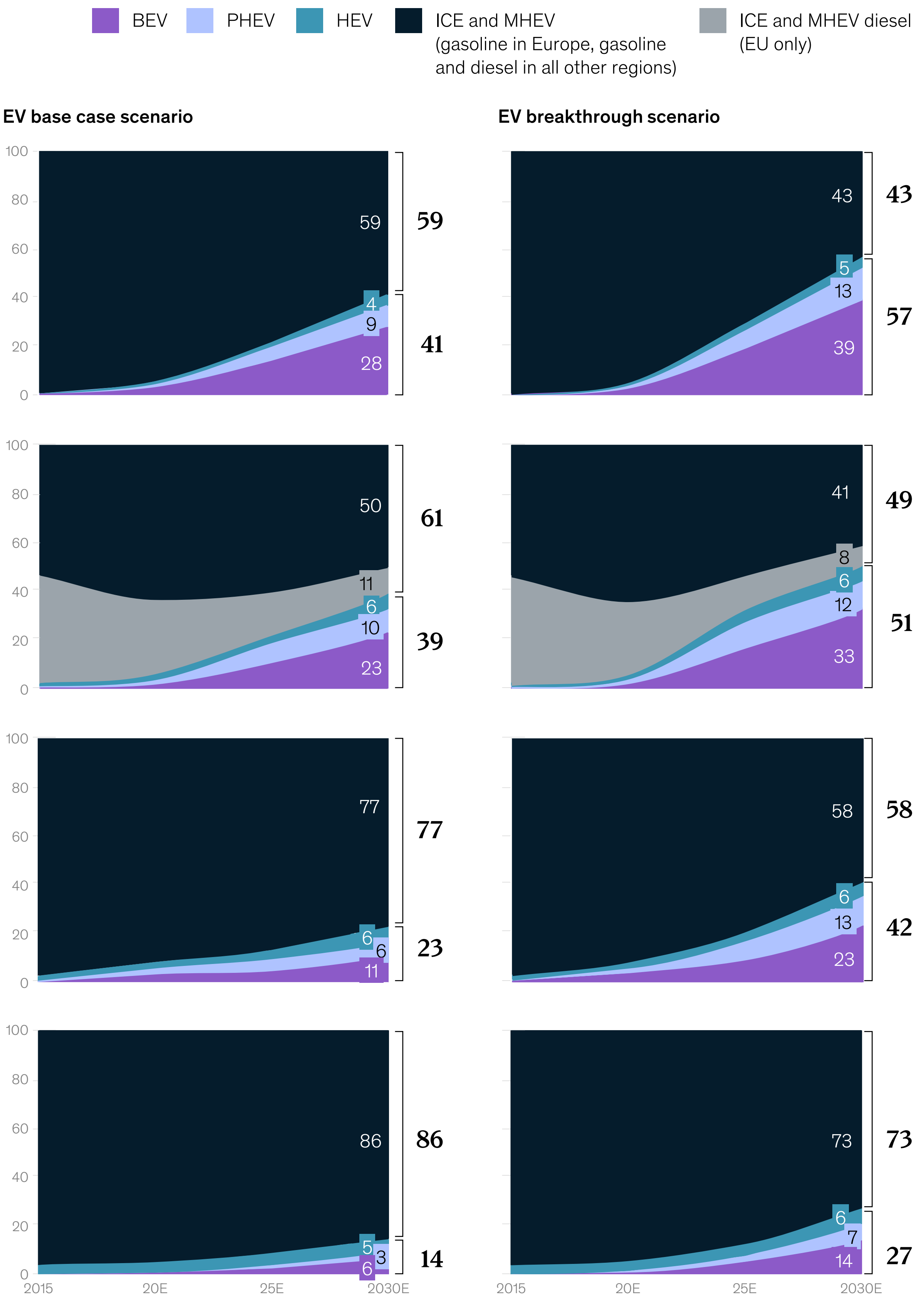
Given the uncertainty of timing and magnitude of EV uptake, we have modeled two scenarios that reflect the relative uncertainty in (city-level) regulation, infrastructure rollout, customer acceptance, vehicle model availability, and battery technology advancements across regions: a base case, in which EV adoption follows a gradual path, and a breakthrough case, in which all drivers reinforce each other and create accelerated adoption.

While most new vehicle sales after 2030 will be electric, the transition speed per region will depend significantly on the regional peculiarity of these four levers. Exhibit 3 shows the results of the two scenarios.

Exhibit 3

Powertrain mix – different growth dynamics in China, Europe, the US, and RoW

Share of new vehicles sold, percent



Source: McKinsey xEV Powertrain Market Model, McKinsey Center for Future Mobility

We expect China to remain the leading market for bringing EVs onto the road, outpacing growth in all other regions. This growth builds on a track record of having sold approximately 1.2 million light EVs in 2018 (about 60 percent of the global total of 2.1 million units) and is driven by the coherent pull across all four factors of infrastructure, regulatory support, technology push, consumer preferences, and vehicle model availability (61 EV brands available today, by far more than in any other region). In a base case, we expect over 40 percent of vehicles sold in China in 2030 to be electrified, with BEVs being the dominant powertrain technology. We predict Europe will follow China in its EV adoption curve with a projected share of almost 40 percent of cars sold being electric by 2030. Given the changing political landscape and differing regulatory directions both on national level and state level, we see a higher uncertainty in EV uptake in the US. Therefore, we expect the US to have the largest ICE share by 2030.

Throughout the transition period in the next decade, ICE will remain the dominant technology. The scenarios shown above include MHEVs (48V) under ICE vehicles. We expect MHEVs as a share of the remaining ICE vehicles to be 60 to 80 percent in Europe, 50 to 70 percent in China, and 10 to 20 percent in the US by 2025. In 2030, we expect this share to increase to nearly 100 percent in Europe, 70 to 90 percent in China, and 60 to 80 percent in the US. Thus, while combustion engines remain important, a combustion engine vehicle without at least a 48V e-motor becomes increasingly unlikely.

Furthermore, the analysis above includes a (small) share of FCEVs as part of the EV segment. For light-duty vehicles, the development and commercialization of FCEVs lag behind that of BEVs. Similarly, hydrogen refueling infrastructure is being deployed in several leading countries (e.g., Japan, South Korea, China, Germany, the UK, Scandinavia) but lags behind the coverage that chargers for BEVs achieve today. If the technology scales up, it could achieve a similar tipping point to BEVs around eight to ten years later. In heavy-duty vehicles, the situation is different: the higher energy density of hydrogen for FCEVs is well suited for the use case demand of such vehicles; development and commercialization of pure-battery and fuel cell heavy-duty trucks is a close and not yet decided race.

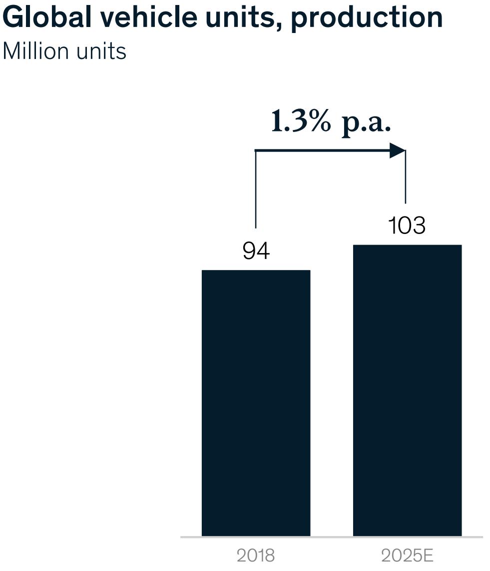
1.3 Dynamic growth outlook – powertrain components will outgrow vehicle market

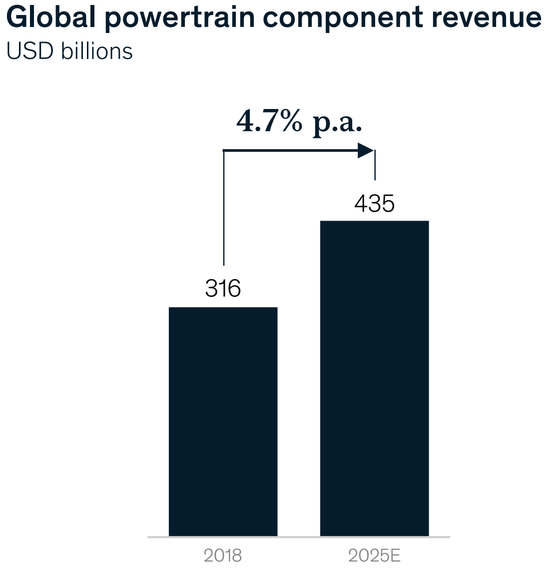
Based on the overall vehicle production growth as well as the shift in powertrain mix described in the section above, we built a detailed, bottom-up model simulating the market development of 28 powertrain component markets. The simulation is based on the evolution of unit sales combined with average industry prices for these powertrain components and subsystems. Our model projects component market revenue broken down by region, vehicle segment, and powertrain type from 2018 to 2025. The following analysis is based on a global base case EV scenario: while the global vehicle market is expected to grow by 1.3 percent p.a. in units by 2025 (base year: 2018), we expect the powertrain component market to grow at more than double that pace, with about 4.7 percent in revenue by 2025, giving rise to new opportunities for suppliers. As such, we estimate the overall powertrain market to reach USD 435 billion by 2025.

Revenue development outgrowing the vehicle market is caused by an underlying shift towards powertrains with higher powertrain content per vehicle (see next section). This can be explained by two factors: more content for hybrid vehicles and EVs via the battery pack and more content per vehicle for ICE diesel powertrains (e.g., through increased turbocharging, 48V electrification, more complex exhaust gas aftertreatment systems). Exhibit 4 compares vehicle unit growth and revenue growth by powertrain technology.

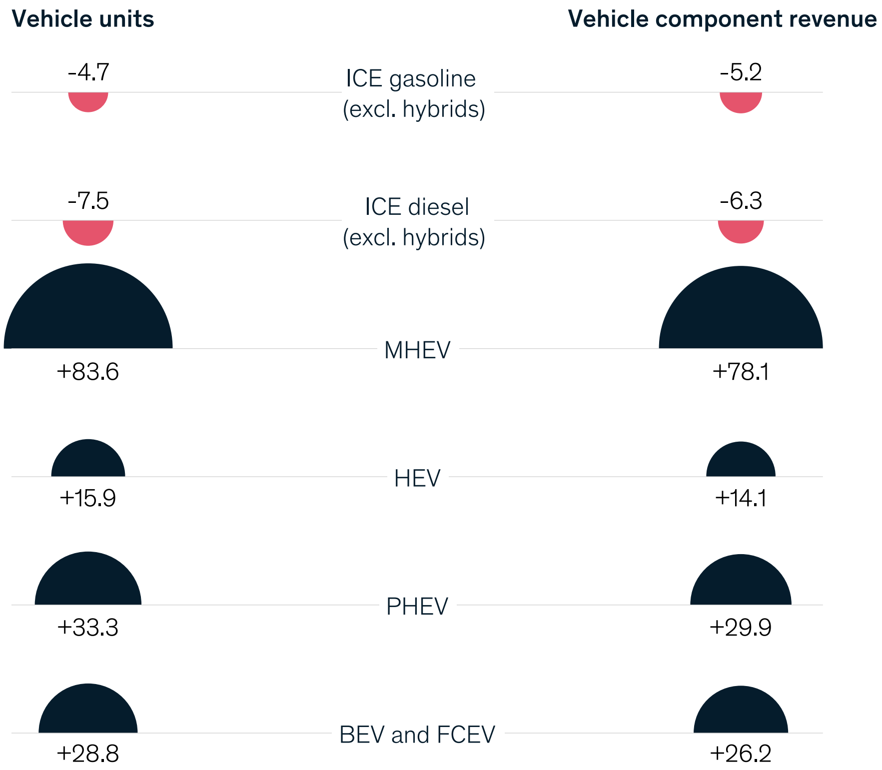
Exhibit 4

Dynamic growth industry – global powertrain revenue exceeds global vehicle units with very different dynamics for different powertrain technologies





Granularity of growth, 2018-25 CAGR, percent



Source: Revenue forecasts based on vehicle volumes from IHS Markit Alternative Propulsion Forecast, August 31, 2019; McKinsey Center for Future Mobility

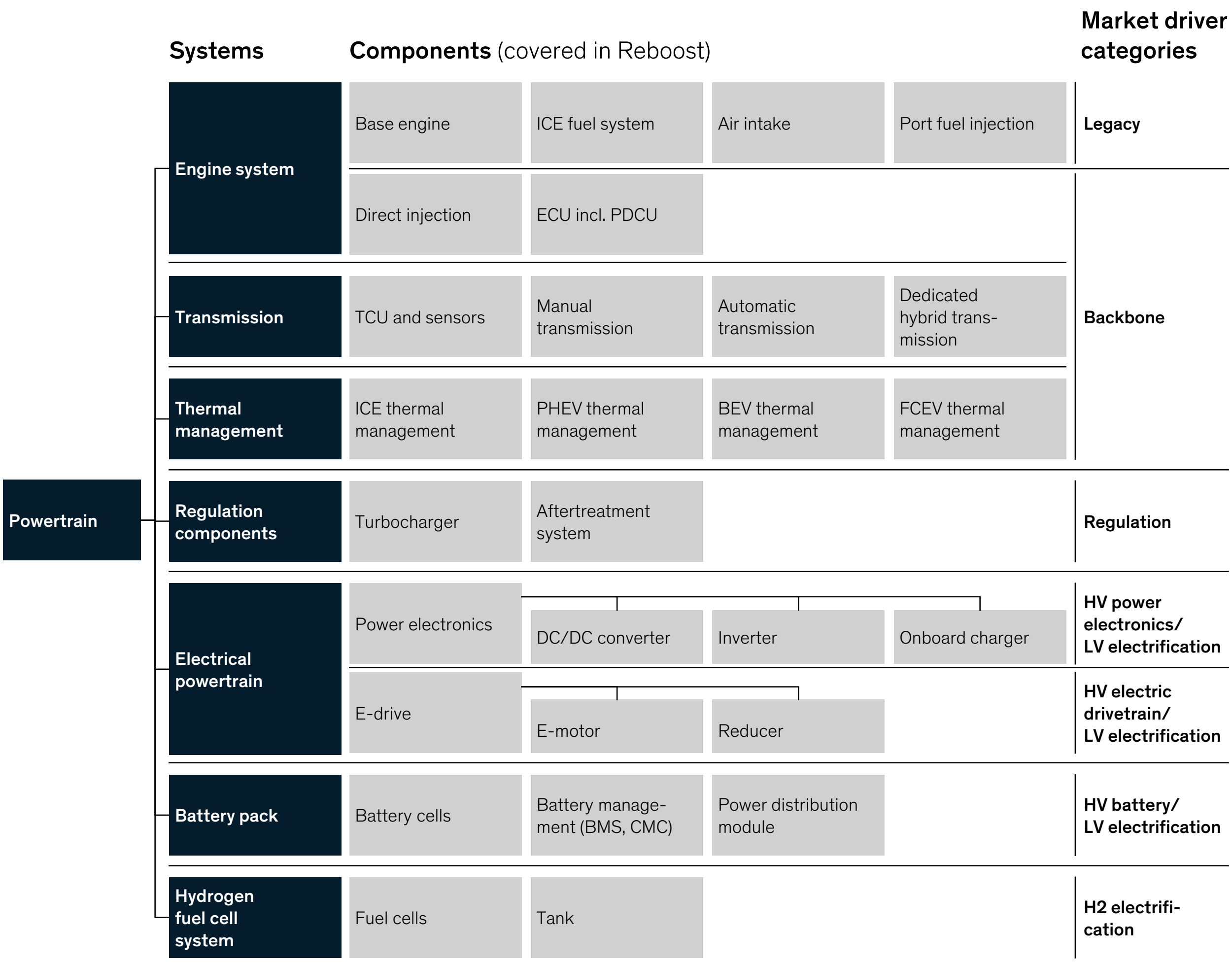
1.4 Outlook on powertrain content per vehicle – identifying pockets of growth in a stagnating ICE market

To understand the development of the component market, we have broken down the powertrain market into seven systems and 28 components (Exhibit 5). These components can be analyzed by market driver categories that explain the underlying component market characteristics, i.e., legacy-, backbone-, regulation-, and LV-electrification-driven markets. An additional cross-cutting category "sensors and actuators," not shown in Exhibit 5, is also taken into consideration.

With regard to ICE powertrain components, we propose a differentiated view on the underlying market drivers. Legacy components are traditional ICE components where only moderate technological innovation is expected and market consolidation will likely start within the next years (e.g., base engine, port fuel injection). Backbone components (e.g., ECU, thermal management, direct injection) require system and/or electronics understanding and

Exhibit 5

Applied powertrain market split



Source: McKinsey Center for Future Mobility

can be a profound basis for the development of next-generation ICE/MHEV powertrains and for the successful transition to alternative powertrains. Regulation ICE components enable better emission performance in traditional ICEs (e.g., aftertreatment system, turbocharger) and their market development correlates with regulatory targets (e.g., CO_2, NOx).

Taking into account these market driver categories, Exhibit 6 shows how the value shift will evolve. Legacy components are expected to slightly shrink already by 2025, and we predict the same for backbone and regulation components by 2030. We foresee the strongest short-term (2018 to 2025) growth in LV electronics components (over 50 percent CAGR) and the HV battery (over 25 percent). The latter will, by far, also constitute the largest value pool, with a market size of more than USD 70 billion by 2025.

Exhibit 6

Outlook 2025 – global pockets of growth

Market size, USD billions

Market size 2018	<0%	0-1.3%	>1.3%
<1			
1-10			
>10			

CAGR 2018-25E

Market driver categories

Global	**Legacy**	**Backbone**	**Regulation**	**LV electrification**	**HV power electronics**	**HV electric drivetrain**	**HV battery**	**H2 electrification**	**Total**
2018 market size 2018-25E CAGR	78.6 -1.1%	172.2 1.1%	39.3 3.2%	0.6 59.4%	4.9 18.8%	4.1 20.3%	16.1 25.7%	0.04 32.3%	315.9 4.7%
Revenue	79%		21%						
	Traditional technologies **6% of total growth 2018-25E**		Regulation-driven and innovative technologies **94% of total growth 2018-25E**						
Components	Base engine ICE fuel system Air intake Port fuel injection	Direct injection ECU incl. PDCU TCU and sensors Manual, automated, and dedicated hybrid transmission Thermal management	Aftertreatment system Turbocharger	LV inverter LV DC/DC LV e-motor LV battery pack	HV inverter HV DC/DC Onboard charger	HV e-motor Reducer	Battery cell Power distribution module (PDM), battery management system (BMS), cell management controller (CMC)	Fuel cells Tank	

Source: McKinsey Center for Future Mobility

By 2025, legacy and backbone components will only constitute 6 percent of the total market growth, most of the growth (i.e., 94 percent) resulting from regulation- and electrification-related (LV and HV) components.

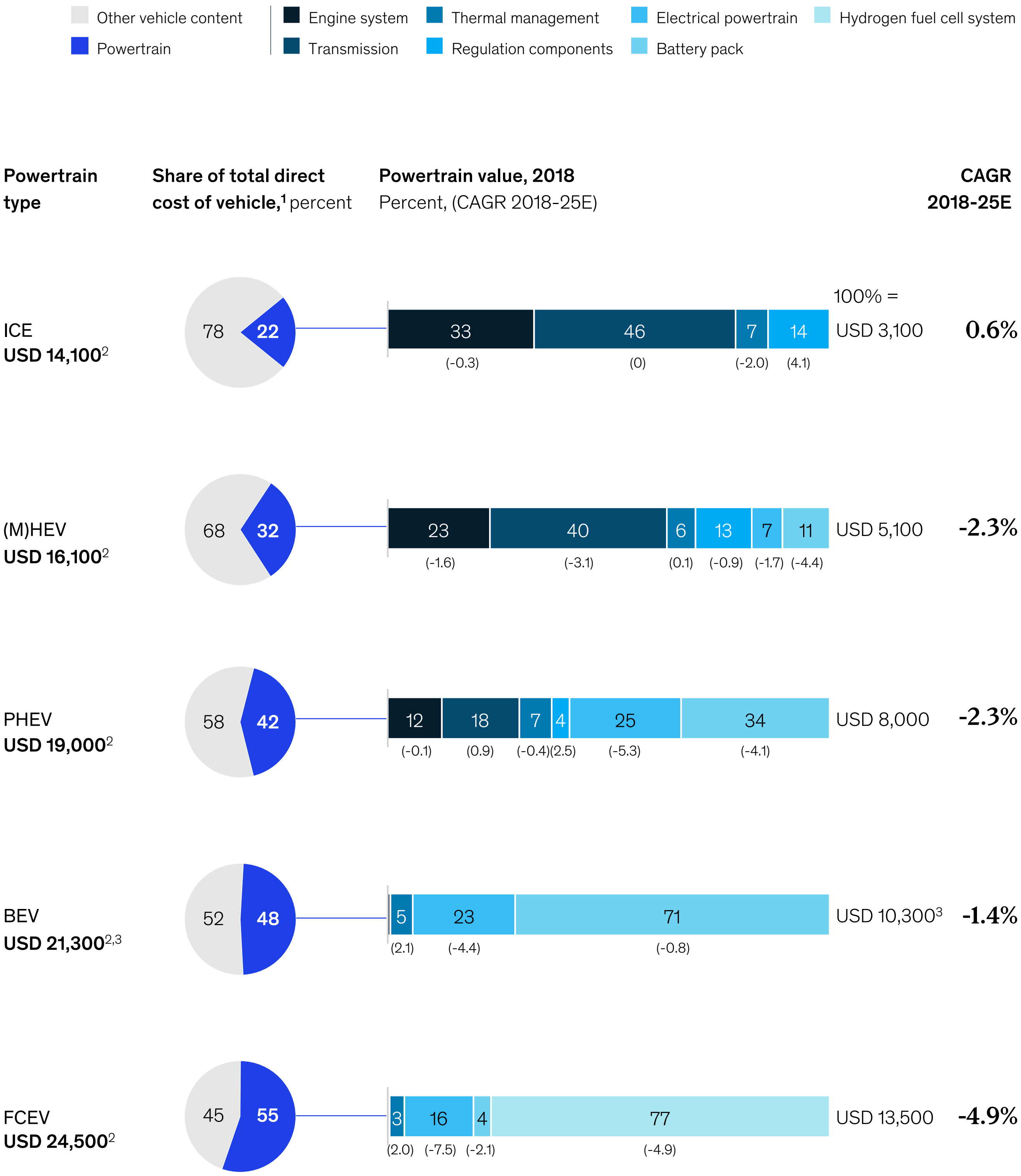
The changes in revenue pools are strongly correlated with the underlying shift in the powertrain mix discussed in Chapter 1.3. This is clearly visible when comparing the estimated content per vehicle (CPV) development until 2025. CPV is defined as value (cost plus markup) of the powertrain components per vehicle.

While over time the average CPV will decrease within each powertrain type considering standard technological and cost developments, we observe two effects leading to the increasing overall revenue pools: a shift to powertrain types with an overall higher CPV. While an average ICE powertrain (assuming a C-segment vehicle) holds approximately 20 percent of the vehicle value at an average cost of USD 3,000, an average BEV powertrain costs approximately USD 10,000 for a vehicle in the same segment (assuming a 50 kWh battery), making up about 50 percent of a vehicle's value today (Exhibit 7). Most of this cost is driven by the battery, but power electronics and e-drive units also hold significant cost shares.

In conclusion, we expect the powertrain component market to grow, but with a fundamental shift in value creation from mechanical to electrical, mechatronic, and electrochemical. Automotive suppliers should manage their portfolio and decide on where and how to participate in this growth. Increased cost pressure on traditional components on the one hand, and high R&D expenditures to enter a highly competitive alternative powertrain market with initially low sales volumes on the other hand, force choices by automotive suppliers. A detailed analysis of each component of the powertrain market follows in the next chapter.

Exhibit 7

The automotive powertrain component market has started to become a different industry – changing from a stable technology to a complex portfolio game



1 For OEM before margin, overhead, taxes, and subventions, but includes supplier margin and overhead
2 Assuming an average C-segment vehicle, for simplification with constant value for non-powertrain part of vehicle
3 Average 40 kWh battery power for a C-segment vehicle

Source: McKinsey Center for Future Mobility

2 Deep dives into the changing powertrain component market

This chapter provides detailed discussions on the main powertrain systems and components. This includes a market assessment, an outlook on market volume and growth until 2025, an overview of the industry structure, key (technology) trends, and success factors for suppliers for each system.

2.1 Engine system – intensified competition in a commoditizing market

Market assessment (Exhibit 8)

Market volume and growth forecast
The engine system component market consists of both legacy and backbone components (see also Exhibit 5). Given their maturity and the increased cost pressure resulting from the anticipated peak and subsequent decline in ICE production, legacy component revenue (air intakes, ICE fuel systems, base engines, and port fuel injection) is growing more slowly than underlying vehicle growth. Growth for backbone components (ECU, direct injection), in turn, still outstrips the growth of the underlying vehicle market.

In fact, the two backbone components represent a promising pocket of medium-term growth. First, the shift from port fuel injection to direct injection for gasoline vehicles – a step that reduces emissions – is expected to continue. While most gasoline vehicles (approximately 55 percent[4]) still used port fuel injection in 2018, by 2025 this balance will have clearly tipped in favor of direct injection (approximately 70 percent[5]).

ECU market growth is driven by increasing software specifications and powertrain complexity. In hybrid powertrains, for example, additional powertrain domain control units (PDCUs) coordinate the torque share of the e-motor and combustion engine. In the future, PDCUs will take over further functionalities, such as energy and thermal management.

Among the legacy components, we expect the strongest growth for the air intake market, driven mainly by expected technological developments such as air intake intercoolers. But we foresee almost no or negative growth in the medium term for the ICE fuel system and base engine markets: revenue is expected to shrink both for ICE fuel systems (-0.2 CAGR from 2018 to 2025) and base engines (-1.8 percent CAGR from 2018 to 2025). This development is driven by two factors: first, base engine cost correlates more strongly with the number of cylinders (and is, thus, influenced by downsizing trends), and second, we expect more technological developments such as crankcase ventilation in the base engine. Due to the influence of engine downsizing and increasing cost pressure in a mature market, commoditization is expected in the base engine market as well. The strong decrease of the port fuel injection market is caused by the shift to direct injection.

4 IHS Markit, Alternative Propulsion Forecast, August 31, 2019, https://ihsmarkit.com/products/automotive-light-vehicle-alternative-fuel-propulsion-forecasts.html.
5 Ibid.

Exhibit 8

Market assessment of engine system components

	Market size, USD bn 2018	Market size, USD bn 2025E	CAGR 2018-25E, percent
ECU incl. PDCU Controls all processes in engine, injection, aftertreatment system, and fuel system. Ensures optimal engine performance	7.3	9.1	3.3
Direct injection Used both in gasoline and diesel vehicles with improved fuel efficiency as compared to port fuel injection	10.8	13.1	2.9
Air intake Provides the oxygen for the combustion process as part of the engine. Regulates intake air temperature	14.5	15.2	0.7
ICE fuel system Manages storage, supply, and monitoring of fuel delivered to the combustion engine and contains the low-pressure components of the engine as well as the evaporation system	13.5	13.3	-0.2
Base engine Engine block, incl. crank shaft, piston, and engine head. Most strongly affected by downsizing trends	49.5	43.7	-1.8
Port fuel injection Indirect injection only applicable in gasoline vehicles. Declining technology with share from 40% take rate in 2019 to 25% in 2025	1.1	0.6	-9.8

1.3% vehicle market

4.7% powertrain market

Source: McKinsey Center for Future Mobility

Industry structure
While the base engine is typically produced by the OEM, engine system components described above are manufactured by suppliers. The engine system market volume and industry structure differ by engine component. The injector market is quite consolidated, with the top three suppliers providing roughly more than two-thirds of the market. Suppliers need to closely collaborate with OEMs in R&D to improve combustion efficiency, enable next-generation fuel efficiency, and understand engine and aftertreatment systems.

The ECU market is an established market, with the top five players representing approximately more than two-thirds of the market. Suppliers typically develop the hard- and base software and OEMs the application software.

The air intake market is expected to commoditize for simple air intake modules, while differentiation possibilities will remain for advanced air intake modules (e.g., integrated cooled air intake). In consequence, the air intake market is moderately consolidated, with the top six players accounting for about half of the market.

The fuel system market (excluding the injection market and high-pressure pumps, Exhibit 8) is mature, with low entry barriers due to relatively few technology requirements. OEMs tend to vet and engage multiple suppliers to ensure competition and supply chain stability, contributing to fragmentation in the supplier market. As a result, the market contains a large number of small- and medium-sized players.

Finally, the base engine is mainly assembled by OEMs, that in most cases outsource raw parts and metal cast production. We see a general trend towards further outsourcing of metal casting and could imagine an increased number of joint engine development projects between several OEMs to share investments.

Key trends
Several major trends will shape the engine system component market:

— *Fuel efficiency optimization in fuel injection.* Fuel efficiency has implications for the performance of fuel injection components. Specifically, injection pressure for diesel and gasoline vehicles will need to be raised to improve fuel atomization, which will lead to a more efficient combustion process. High-pressure direct injection may also result in increased emissions of fine particulates, which need to be controlled via the aftertreatment system. The higher pressures require elements in the engine to reduce vibrations caused by combustion, such as a balancer shaft and reinforcement of cylinder components. As a result, optimizing fuel efficiency leads to higher costs for other engine system components. Due to advances in materials, however, today's advanced plastics can withstand higher temperatures and pressures. This enables the use of special lightweight plastics for engine-covering parts, such as air intake modules, somewhat reducing the added costs (and weight) associated with fuel efficiency.

— *More software features in engine management.* Ensuring robust emission control under varying operating conditions requires more complex software applications. Tightened emission regulations under real driving conditions and more sophisticated combustion and aftertreatment systems also cause additional software complexity. Modular software architectures applicable to different engines and vehicles enable suppliers to limit development costs. Furthermore, a gradual shift from vehicle and engine testing to digital engine applications and testing is in progress to manage complexity in combustion and emission control testing.

— *More advanced cooling solutions in air intake.* As turbochargers become more common, air intake systems will see a rise in advanced cooling solutions, e.g., direct air cooled, indirect (water cooled), or integrated cooling (large plastic manifold around the cooler). While we observe an overall trend towards integrated cooling (in combination with turbocharging), complex non-cooled intake manifolds with fixed or variable runner lengths will decline in market share overall.

— *Better evaporation management in ICE fuel systems.* There is also a trend to improve evaporation management, ie., lowering the level of fuel fumes emitted into the environment to comply with local EVAP regulation. While pressurized tanks are already being installed today, this trend will rise further. Pressurized tanks decrease evaporation after long distances of purely electrically propelled travel. Furthermore, additional pumps integrated into the evaporation systems are expected in the future. This will increase purge performance and is due to cost and performance considerations mainly expected in premium vehicles; however, valves will be sufficient for most evaporative systems.

— *Further engine component integration.* Finally, more compact system design is expected for the powertrain in ICE vehicles. This is especially true for HEVs, where the additional e-powertrain components lead to decreased space availability and the increasing need to further optimize the overall design of the engine component and integrate the different parts of the powertrain.

— *Downsizing the base engine.* Increasingly strict emission regulations will have a direct impact on the base engine. Against the backdrop of higher SUV and large-vehicle sales, the average number of cylinders is expected to decrease overall slightly by 5 percent by 2025.[6]

Success factors for suppliers

In the engine system market, suppliers with long-standing know-how regarding engine reliability, safety standards, and regulatory compliance are likely to continue to win and have the opportunity to serve a larger engine market. Suppliers will have an advantage if they are able to improve ECU software by increasing their internal software expertise or defending their people know-how and market position against OEMs and competitors.

In this context, we see two different options. One is to allow pricing of software separate from that of hardware. The other is to follow a modular ECU and software approach, reusing existing software knowledge and code together with modular ECU offerings in order to acquire new customers (especially in China) who rely on turnkey solutions.

Since we expect the fuel system market to be influenced by peak ICE production, which is approaching fast, overall supplier consolidation is likely. Successful suppliers will be the ones that potentially lead such consolidation: they have largely written off their investments and can consider the engine system market as a source of income.

6 IHS Markit, Alternative Propulsion Forecast, August 31, 2019, https://ihsmarkit.com/products/automotive-light-vehicle-alternative-fuel-propulsion-forecasts.html.

2.2 Regulation components – a critical factor in the future of combustion engines

Exhibit 9

Market assessment of the turbocharger and aftertreatment system

	Market size, USD bn 2018	Market size, USD bn 2025E	CAGR 2018-25E, percent
Turbocharger Uses the energy of the exhaust gas to power a turbine that compresses the engine's intake air and, thus, the oxygen density and effective volume within the cylinders	9.6	12.8	4.2
SCR Applied only in diesel systems where it reduces NOx emissions via selective reduction to nitrogen and oxygen	3.0	7.0	12.9
EGR Redirects exhaust gas into the combustion process in order to reduce the oxygen level in the intake air. Thus, reduces NOx emissions for diesel systems, and gas exchange losses lead to improved fuel efficiency in gasoline engines	2.0	3.3	7.8
Particulate filter Filters soot from exhaust gas. Needs to be applied in diesel and gasoline direct injection systems	9.0	9.9	1.4
Catalytic converter Reduces the amount of toxic pollutants from exhaust gas. Catalytic substrate can be, e.g., ceramic or metallic	13.0	13.5	0.6
Lean NOx trap (LNT) Adsorbs NOx during lean combustion. The trapped NOx is reduced during regeneration of the LNT. Applied in diesel systems only	2.8	2.5	-1.6

1.3% vehicle market

4.7% powertrain market

Source: McKinsey Center for Future Mobility

2.2.1 Turbocharger

Market assessment (Exhibit 9)

Within the context of increased emissions and CO_2 fleet regulations, turbochargers enable engine downsizing while ensuring sufficient power and torque. Turbocharger technology is used in both gasoline and diesel vehicles, with the average price point for gasoline turbochargers usually being lower than that for diesel turbochargers. Although gasoline exhaust is hotter than diesel exhaust – meaning there are higher temperature requirements for the turbocharger turbine and housing – most gasoline turbochargers use less costly wastegate technology than variable-geometry turbochargers (VGTs) in diesel. Hybridization of the powertrain will either positively affect the turbocharger market or have no impact, depending on the region, since the vast majority of HEVs are equipped with turbochargers.

For the purpose of this report, we distinguish between three different types of turbocharger technologies:

— *Wastegate (W/GT).* A basic turbocharger with a release valve for excess pressure in the compression line

— *Variable geometry turbocharger (VGT/VNT).* A more technically advanced turbocharger with an optimized area/radius ratio (A/R) for low- and high-speed driving. A low A/R ratio for low speeds leads to improved turbocharger load, thus reducing turbo lag. A high A/R ratio for high speeds increases flow capacity and thus supports optimal functioning.

— *Electric supercharger.* An electrically powered turbocharger that reduces turbo lag and, thus, supports compression in low-speed situations. Additionally, it saves energy in braking mode by slowing down the turbocharger.

In general, the number of turbochargers per vehicle will increase. Some engines will further contain two turbochargers, either in parallel (bi-turbocharger) or in a sequential setup (twin-turbocharger). Up to four turbochargers per vehicle (quad-turbocharger) are possible. Installing multiple turbochargers – in different sizes, but all smaller than single turbochargers today – will further optimize turbocharger performance. While total power will remain the same, the reduced inertia of smaller turbochargers will make it easier for them to spin in transient modes. Furthermore, an improved torque delivery curve is possible at different engine speeds with a smaller turbocharger adapted to low engine speeds and a larger one adapted to high engine speeds.

Market size and growth

Revenue from turbocharger sales is expected to rise globally through 2025 (Exhibit 9) as an increase in content per vehicle can be expected to outpace the decrease in unit price. We will likely see a boost in the relative market share for gasoline turbochargers, with higher content per turbocharger than their diesel counterparts. As downsizing requirements are raised, more (complex) turbochargers will be used to compensate for the lower power of smaller engines. Technology shifts from wastegate to VGTs and electric superchargers, which will drive revenue growth for suppliers. We consider turbochargers to be one of the key levers for reducing consumption and emissions in combustion engine and hybrid vehicles while maintaining engine performance. Revenue development in the turbocharger market will vary by region. Greater China and South Asia are expected to see the most revenue growth (more than 7 percent and 5 percent, respectively) due to a downsizing trend for gasoline vehicles (-1.1 percent CAGR for average cylinders in gasoline vehicles in Greater China, from 2018 to 2025[7]) and strong vehicle growth (approximately 4 percent CAGR for combustion vehicles, including hybrids in South Asia, from 2018 to 2025[8]), respectively. Further downsizing of combustion engines will lead to stricter technological requirements for turbochargers, which will increase CPV.

7 IHS Markit, Alternative Propulsion Forecast, August 31, 2019, https://ihsmarkit.com/products/automotive-light-vehicle-alternative-fuel-propulsion-forecasts.html.

8 Ibid.

The overall downsizing trend and relatively low penetration of turbochargers in North America today provides a basis for expected revenue growth of over 4 percent until 2025. Because turbocharger penetration is already strong in Europe, growth rates will be lowest in that region.

Industry structure
The turbocharger market is a well-established supplier market, with the top four suppliers accounting for the majority of global revenue. China has few local suppliers, but US and European suppliers both have a strong local presence.

In the turbocharger industry, OEM-supplier interaction takes a specific form. OEMs must manage a balancing act between fulfilling regulations and satisfying customer demand for increasing engine performance. Suppliers, in turn, have gained the know-how to develop the next-generation turbocharger, helping OEMs to improve on both dimensions. The turbocharger market is considered a control point for suppliers in the combustion engine market, with high barriers to entry given long-term OEM contracts, high R&D investment, precision engineering, and a need for system understanding.

Key trends
Several recent technological advancements are shaping the next generation of turbochargers:

— Lightweight materials are making it possible to substantially decrease turbocharger weight while boosting vehicle efficiency.

— Performance improvements, such as increasing the capacity of turbochargers with a design that enhances air volume throughput, are at the center of technology trends. Alternative geometries, such as those used in VGT, also boost performance, and manufacturers are shifting to them more and more.

— Electric superchargers can lower emissions (with decreased turbo lag), even with stop-and-go utilization (urbanization).

— Bi- and twin-turbochargers are the focus of current development efforts to reduce turbo lag, boost performance, and cover a wider range of engine speeds.

Success factors for suppliers
As regulation increases, technological developments will be key to success. With intrinsic system knowledge, including expertise on thermodynamics as their prime asset, the established tier-1 turbocharger suppliers meet this condition.

For such suppliers, the turbocharger market remains generally promising in terms of revenue. The trend towards increased engine performance with lower engine displacement together with OEMs' heavy reliance on supplier technical expertise and system understanding are driving a near-term supplier market growth for turbochargers. Its growth rate turns out to be three times the rate of the vehicle market overall.

2.2.2 Aftertreatment system
Market assessment (Exhibit 9)
Market size and growth
Growth for the various components of the aftertreatment market ranges widely, from approximately -2 to 13 percent CAGR through 2025 (Exhibit 9). This high variance is due to the different current and future penetration levels of the various aftertreatment systems in the combustion engine market. We considered the following aftertreatment systems in our analysis:

— *Selective catalytic reduction (SCR) in diesel vehicles.* The use of SCR will increase in all diesel systems, either instead of or in addition to lean-NOx-trap catalysts (LNTs). While the combination of an SCR with an LNT system is standard in mid- and high-range cars today, in 2025 we expect a second SCR to replace the LNT in 20 to 25 percent of these vehicles. For low-range cars, an SCR in addition to an LNT will be standard in about 70 percent of the vehicles. Thus, the SCR market is expected to outgrow the powertrain market, while the LNT market will stagnate.

— *Exhaust gas recirculation (EGR) in gasoline vehicles.* Gasoline vehicles constitute the biggest growth market for EGRs. While their penetration is very low today, it will increase to 15 to 30 percent by 2025. EGRs are used in gasoline systems to raise fuel efficiency and thus reduce a vehicle's CO_2 emissions. In consequence, participation in the gasoline EGR market may be attractive for suppliers, especially in the long term as the diesel vehicle market is expected to decline.

— *Particulate filters and catalytic converters.* These are already used in both diesel and gasoline vehicles today (where growth in particulate filters is mainly caused by application in direct-injection gasoline engines). Growth in both aftertreatment components is driven by increasing CPV (i.e., higher complexity of aftertreatment system for particulate filters, application of more expensive electric catalytic converters, and larger share of precious metals for catalytic converters; see "Key trends" section) as well as by the development of the underlying vehicle market.

Regional trends differ more significantly in the aftertreatment system market than they do in the markets for other components. The largest market is Europe, but as penetration is already high, we expect no further growth and even a slight decline in this region. The market growing the most is China, where we also find a push towards stricter and more strongly enforced emission regulations. The US market is the second-largest driver of volume growth at 2.5 percent p.a. from 2018 to 2025, mainly due to higher NOx regulations, leading to a continuous increase in CPV and EGR uptake.

Industry structure

The aftertreatment system market is an established supplier market, with only a limited number of full system suppliers. New entrants would be confronted with the need for large capital investments and significant technical requirements on their products to comply with environmental legislation.
On the demand side, strong differences are evident in OEM purchasing trends from one region to another. Chinese OEMs lean towards purchasing whole-system solutions, while European OEMs, with in-house knowledge of system optimization, tend to source single components and manage the system integration.

Key trends

For aftertreatment systems, key trends are mainly driven by the future development of emission norms. New testing procedures require OEMs to apply state-of-the-art technology. Thus, successful suppliers are engaged in strong R&D efforts to offer system solutions with innovative technology to OEMs, making these suppliers a cornerstone to optimization of the combustion engine market in the 2020s.

— *More monitoring due to more stringent emission regulations.* As emission regulations tighten, we expect the number of sensors to increase in all combustion engines in order to more closely monitor real-traffic emissions and the impact of aftertreatment systems. Future emission legislation will force OEMs to employ two or more NOx sensors. Stronger capabilities in real-time computation (Chapter 2.3, TCU) will further improve the precision of the aftertreatment system. Further sensors detect O_2 (lambda sensors), EGR temperature, pressure, and SCR levels. This development will lead to significantly growing aftertreatment CPV.

— *Increased efficiency to fulfill more stringent emission regulations.* Greater efficiency will mainly be achieved by expanding the operating-temperature window, in particular after engine start, when coasting, or in low-speed situations. SCRs with copper-based zeolites can also operate at broader temperature ranges compared to current iron-based zeolites. For catalytic converters, low-temperature emission reduction can be achieved by:

  - Electrically heating the catalytic converter (additional heat module increases costs)

  - Placing the catalytic converter closer to the engine so that it heats up faster. Weight and cost are reduced as a result because system layout is simplified, but installation in the engine bay becomes more complex.

  - Combining two SCRs, with one SCR closer to the engine (for increased heat exposure) and one located further downstream

  - Replacing the ceramic substrate with a metal one, which reduces heat capacity and, thus, allows the complete converter to heat up faster.

  - On the system level, integrating several aftertreatment components into a single system (e.g., LNT and SCR or catalyst; particulate filter and SCR) has several benefits over traditional solutions: stronger heat concentration, improved efficiency, and significant weight reduction.

— *Cost reduction efforts.* Design decisions (wash-coat design, smaller size due to turbulence-generating structures) will reduce the amount of precious metals in catalytic converters. Additionally, simplifying the general layout and design of the aftertreatment/ exhaust system can further reduce costs.

Success factors for suppliers

Aftertreatment component suppliers can take two steps to increase their chances of success in the shifting market. First, using their R&D strengths in partnership with OEMs, suppliers can be first to market in aftertreatment innovations and help OEMs fulfill emission norms.

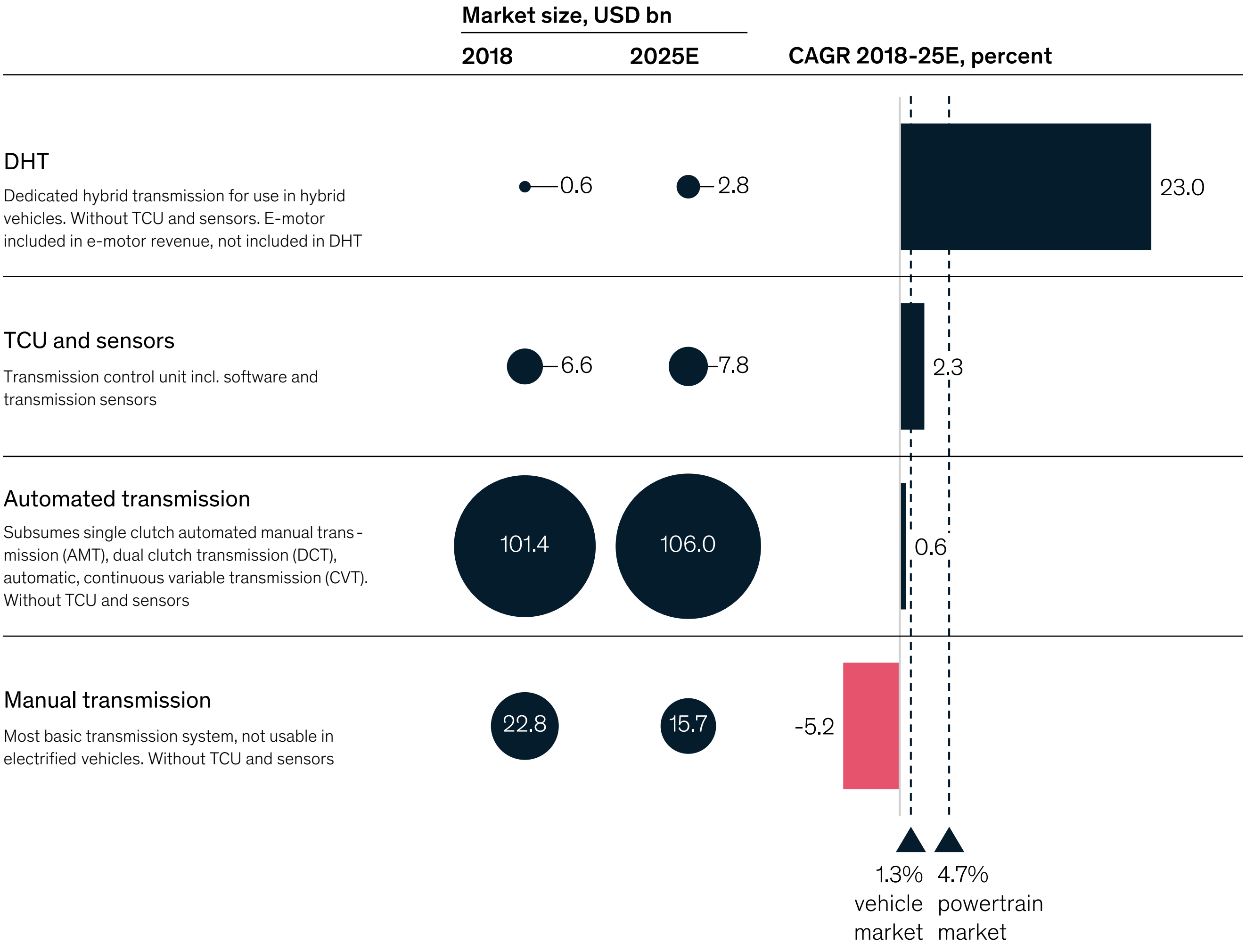
Second, with superior system understanding, suppliers can differentiate themselves through end-to-end emission control solutions for combustion, EGR, and aftertreatment. Sensor and ECU software capabilities will enable suppliers to understand and optimize the aftertreatment system.

2.3 Transmission – the backbone of hybridization

Market assessment (Exhibit 10)

Exhibit 10

Market assessment transmissions



Source: McKinsey Center for Future Mobility

Market volume and growth forecast
The transmission market is forecast to stagnate with an overall CAGR from 2018 to 2025 of 0.1 percent due to increased penetration of automated (CAGR 0.6 percent) and hybrid transmissions (CAGR 23.0 percent) as well as a decline in manual transmissions (CAGR -5.2 percent). Within the market, variation is evident across the three transmission types: manual transmissions, automated transmissions, and dedicated hybrid transmissions (DHTs). The DHT market is driven by the development of the underlying xEV market. The market for transmission control units (TCUs) is growing faster than the transmission market overall as hybridization becomes more common and functional complexity and software requirements increase as a result.

Industry structure

The transmission market is an established market with OEM in-house production and four major suppliers. In the future, OEM in-house share may increase further due to freed-up ICE development and production capacity. Cost pressure will grow for pure ICE and MHEV transmissions due to the post-2017 decrease in the volume of pure-ICE vehicles and the expected post-2025 drop in all ICE vehicles, including HEVs.

Key trends

Trends in transmission technology will improve fuel efficiency, while electrification will bring a more complex mix in case of hybrid transmissions and strong simplification in transmissions:

— *Fuel efficiency.* The number of gears will likely increase, peaking at around nine, the point at which economic returns would be expected to diminish. This development further optimizes the match between engine power and gear ratio, improving both fuel efficiency and the overall driving experience. Better gear-shifting electronics and software are anticipated as well, along with an increased shift to lightweight housing materials, such as aluminum, that can withstand higher forces and torque momentum.

— *Electrification trend.* For HEVs, we expect an increasing shift to dedicated hybrid transmissions. These transmissions are an extension of common automated transmissions and are designed exclusively for hybrid systems. Requirements for mechanical transmissions will decline as the reverse gear is omitted and the e-motor becomes part of the transmission. A BEV, in turn, does not require a conventional transmission system, but only a reducer, which can be combined together with the e-motor in an integrated e-drive system (Chapter 2.4).

— *Autonomous driving.* Growth in autonomous driving in the medium- to long-term future will lead to an additional push towards the adoption of automatic transmissions.

— *Material and integration.* Further trends will be overmolded microelectronic assemblies and next-generation BD-HDI (Bare Die – High Density Interconnect) electronics will include increased integration of actuators, sensors, and electronics into a single unit.

Success factors for suppliers

We identified two main success factors in the transmission market: first, managing of the increasing complexity with regard to R&D and production of automated classic and hybrid transmissions, and second, cost excellence especially for simple BEV reducers.

Suppliers can respond to the increased complexity of classic and hybrid transmissions in two ways. First, excellence in powertrain system understanding is the basis for ensuring an optimal and efficient interplay of mechanical, electrical, and electronic components. This powertrain system understanding also allows suppliers to transfer their knowledge into TCU software development, which may further increase powertrain performance. Second, suppliers will likely build a modular portfolio that allows them to offer solutions for a range of electrification types while keeping complexity at a minimum. Doing so will allow transferring knowledge among the different powertrain types, which will also potentially lead to a shorter time to market.

For simple reducers, both cost leadership and system understanding is key. In this context, competence in gearing layout design and dimensioning can be an advantage since a lack of competence increases the risk of failure due to overdimensioning or -sizing of transmissions. Furthermore, experienced suppliers have an edge in terms of reliability, tribology, noise control, and cost. Thus, it will be key for transmission suppliers to offer OEMs small, efficient system solutions for new BEVs and HEVs that will both save space and maximize fuel efficiency.

2.4 Electrical powertrain – maximization of system integration

2.4.1 Power electronics

Market assessment (Exhibit 11)

Exhibit 11

Market assessment of power electronics and e-drive

	Market size, USD bn 2018	Market size, USD bn 2025E	CAGR 2018-25E, percent
DC/DC converter Transforms between 2 different DC voltages, e.g., providing onboard power for 12V components	0.7	4.7	30.9
Onboard charger Necessary for PHEV and BEV and incl. vehicle junction box (VJB); 3 types exist: inductive, conductive, and robotic charging	0.9	4.6	26.4
Inverter Transforms DC (battery) to AC (e-motor) and includes e-motor's ECU	3.4	12.0	19.7
E-motor Propels hybrids as well as BEVs and FCEVs–with its purpose starting at recuperation (start/stop ICE vehicles) up to BEV/FCEV propulsion	3.0	12.7	22.8
Reducer Single-stage gear reducer, applicable in BEVs and PHEVs. Without TCU and sensors	1.2	4.3	20.5

1.3% vehicle market

4.7% powertrain market

Source: McKinsey Center for Future Mobility

Market size and growth

Markets for all power electronics components are expected to significantly outgrow the overall powertrain market (by factors of three to six) due to strong growth of the hybrid and electric vehicle market. Regionally, we expect the strongest growth in Europe and Greater China, with annual growth rates of up to 45 percent for power electronics components.

In terms of average market prices, we expect them to decline for inverters, DC/DC converters, and onboard chargers due to two developments: first, OEMs have announced an increasing number of volume segment EVs for the coming years, which require lower performance specifications. Second, manufacturing costs will fall due to continuous improvements in production, higher yields, and deep localization.

Industry structure

While certain OEMs are currently trying to get a foothold in the power electronics market, we expect a typical tier-1 or tier-2 supplier market for power electronics in the medium to long term. The DC/DC converter, inverter, and onboard charger markets will move from a high-specification, low-volume market to a mass market with standard specifications and modular designs. For onboard chargers with higher levels of system integration, we expect OEM insourcing for selected premium HV vehicles. In these cases, the integration into battery pack in-house by OEMs will allow for IP protection and optimization of the charging system. For lower-tech DC/DC converters and inverters, there is no OEM insourcing trend expected.

Market growth will be driven by OEMs with a need to address lower market segments with despecified products. Additionally, there is high competition in power electronics due to many suppliers currently aiming to enter this market.

To date, customers are unlikely to pay a premium for EVs, although the TCO can be lower at high annual driving miles. OEMs today find profitability with EVs difficult since they need to replace an ICE powertrain with an electric powertrain that is USD 5,000 to 13,000 more costly (depending on the aspired range and, therefore, battery size). We expect the resulting cost pressure to affect the entire EV value chain, leading to price pressure on suppliers that may, as a result, also struggle to make a profit with power electronics components before they reach significant scale.

Key trends

Trends in both materials development and enhanced functionality are expected to shape the development of the power electronics component market:

— *Materials development.* Semiconductors play a crucial role in all three power electronics components. Replacing the silicon oxides in semiconductors with silicon carbides (SiC) raises power density, reduces waste heat, and improves performance efficiency. Specifically, when supported by complete systems, silicon carbide allows for higher voltage levels (up to 800V) and, thus, more power density. This increases transferrable power at any given time and, as a result, enables a decrease in charging times. Two other benefits drive cost reduction: smaller cable diameters throughout the vehicle and less waste heat, which facilitates optimized thermal management and design.

— *A prerequisite for the transition to SiC materials is the general technical improvement of capacitors and coils for increased temperature and power density resistance.* By 2030, another material replacement in semiconductors is likely when GaN semiconductors (or an even larger bandgap material, e.g., diamond) replace SiC for an additional boost in power densities.

— *Shift to an integrated power box.* In the future, we expect an increasing integration of power electronics components, i.e., DC/DC, charger, heater, and power distribution module in one power box. This trend is driven by cost savings through enhanced packaging, cooling, and shared power electronics. For example, integrating DC/DC into the onboard charger is likely to gain a significant market share in the future (most likely a quarter to half of the market by 2025).

— *Increased functionality.* Improvements in design and self-diagnostic functionality can both extend the lifetime of power electronics components and boost user safety. It is also expected that higher power densities from the semiconductor optimization described above will decrease charging time significantly.

— *Potentially relevant innovations.* Two trends are currently considered highly uncertain and/or niche applications: inductive charging and galvanic connected power modules (replacing the galvanic isolated power transfer).

Success factors for suppliers

Suppliers of power electronics components can look to four success factors as they prepare for an evolving powertrain landscape:

— *Cost leadership.* By using their design and production know-how, successful suppliers can lower the cost of power electronics components. Specifically, they can implement fast industrialization and stable production processes with high yield and find low-cost production locations. We expect "deep localization" in China, i.e., sourcing of tier-2+ components (e.g., semiconductors) and manufacturing equipment in China, to become a success factor for setting global cost standards for power electronics components. In addition, a tightening of relationships with semiconductor suppliers will be beneficial to ensure steady supply and best cost of IGBTs (insulated-gate bipolar transistors).

— *Modularization.* Power electronics component suppliers should develop a strong modularized platform. As this market is expected to commoditize, modularization will help save R&D, sourcing, and production cost per piece while enabling a certain degree of product customization. Furthermore, a simplification of components and higher overall integration level will reduce material and manufacturing costs.

— *Design to market specifications.* Suppliers ideally develop one base design that can be adjusted modularly to different customer performance and lifetime requirements to avoid overspecification and unnecessarily high costs. Inverter performance is estimated to develop towards the 150 to 200 kVA class for the majority of OEMs from 2018 to 2021.

— *System knowledge.* In addition to optimizing costs, power electronics component suppliers can also apply their automotive system understanding to enhance performance, e.g., designing power electronics components such that they interlink optimally with the e-drive and, thereby, increase electric powertrain performance and efficiency. Suppliers that can provide the required ECU and software to improve the interplay between power electronics, batteries, and e-drives will likely have a competitive advantage.

2.4.2 E-drive

Market assessment

The e-drive transforms electrical energy into mechanical energy and is composed of the e-motor, reducer, and, in most cases, inverter. For LV applications, the e-motor and inverter are almost always combined as a system solution. For HV systems, there is a large variety of application architectures. Examples include different series of hybrid layouts (ICE and e-motor connected in a series), parallel hybrid layouts (ICE and e-motor connected with fixed speed ratio can provide torque to final driving, separately or together), or central e-drives for BEVs.

Market size and growth

The pure e-motor market is expected to grow 22.8 percent annually from USD 3.0 billion to 12.7 billion by 2025, driven by accelerated penetration of PHEVs and BEVs. Both PHEVs and BEVs can be equipped with similar e-drive concepts.

Industry structure

Currently, OEMs are exhibiting the full range of sourcing strategies. Some are insourcing the entire system, others are outsourcing several subsystems of the drive (mainly inverter and/or e-motor), and others are outsourcing the entire e-drive. Additionally, JVs between OEMs and suppliers are emerging to produce e-drives. We expect approximately more than half of the entire e-drive market in 2025 to be addressable for suppliers.

A dynamic supplier landscape is emerging with four categories of suppliers entering the market, either alone or in some form of partnership or JV: existing tier-1 suppliers, tier-2 OEMs, non-automotive players, and electronics suppliers. Currently, there are more than 15 suppliers developing integrated e-drives for EVs. In the long run, we expect only a handful of leading e-drive suppliers to reach global scale and, therefore, cost competitiveness.

Key trends

A competitive market environment fosters technological innovation for e-drive systems. Several trends can be observed already today that will become more prominent going forward.

— *Material development.* The development and application of new materials will reduce the weight of e-drives and decrease the cost and environmental impact of their production. A focus on research into alloys is expected to lead to the application of a lightweight-material housing. The use of such lighter materials, e.g., aluminum, and more powerful winding materials, e.g., carbon, will improve the performance of e-drives. Wider use of permanent magnets has the potential to boost performance due to reduced complexity while increasing costs through the use of and need for rare-earth materials. At the same time, permanent magnets facilitate the use of recycled rare-earth materials.

— *Production optimization.* Permanent magnets also serve the purpose of honing manual manufacturing processes by improving the standardization of the magnetic properties of the materials. Additionally, better winding processes, e.g., denser winding of coils, leads to higher power density.

— *More modularization.* Automotive suppliers are focusing on an increased modularity of design, i.e., for different power classes to reduce complexity and costs. Modular platforms will also enable more synergies between P0 and Px (different hybrid architectures) systems, allowing the supplier to offer both systems competitively.

— *Higher efficiency through system integration.* With the integration of the inverter, reducer, and e-motor into an e-drive, the continuous efficiency improvement will be at the center of development and can, for example, increase the xEV range at a given battery capacity. In this context, reducers might become more complex with the potential reintroduction of two or three gears. In addition to the integration into an e-drive, some OEMs might purchase an integrated system comprised of an e-motor, power electronics, and transmission, especially for hybrid and low-volume vehicles. This would enable, for example, a reduction in housing size as well as better mechatronic system integration of electric/electronic and mechanical components. This, in turn, would likely result in cost savings, emission decrease in urban settings (combustion engine operating only at high velocities), and an overall efficiency improvement.

Additional functionalities and components can be integrated into the e-drive system to reduce interfaces and allow for optimization at a higher system level. For example, integrated brakes have the potential to be advanced in terms of corrosion and particulate matter emissions, and integrated vehicle control units (VCUs) or ECUs can generate cost advantages through component sharing (e.g., PCB, connector, processor) with the inverter.

Success factors for suppliers

— *Motor design competence.* Suppliers with competence in sizing/dimensioning and optimal design of stator, rotor, axle, and bearings can use their knowledge to impact the vehicle's performance positively. Additionally, employing modern architectures (e.g., axial and transverse flux e-motors), permanent magnet, and synchronous instead of asynchronous motors (replacement of electric windings with permanent magnets) can lead to improvements in cost, performance, and motor control.

— *Tribology.* Although e-drives are equipped with only one to two gears, competence in gearing layout/design and dimensioning is key, as lack of know-how can lead to overdimensioning/-sizing and/or risk of failure. Experienced players in transmission can use their clear advantage in reliability, tribology, noise control, optimum layout and sizing, as well as cost.

— *Power electronics and semiconductors competence.* The inverter is a core component of an e-drive, converting direct current (DC) into alternating current (AC) at a desired output voltage and frequency. This conversion is commonly achieved by a power module containing semiconductor switching devices, i.e., IGTBs. Suppliers can source power modules externally, yet system efficiency of internally optimized power modules are usually higher and the associated cost lower. The power module is one of the most costly parts of an e-drive, and suppliers that have built relevant internal skills in integrating IGTBs into power modules can both enhance the interplay of an inverter with the e-motor and achieve lower total system costs.

— *Systems competence.* Understanding the system and designing/sizing each interdependent component are essential to an e-drive supplier's ability to optimize overall system efficiency from both a performance and a cost perspective. The mechatronic system integration of the mechanical components with the electric and electronic parts as well as the connection to the battery/energy source and the axle/shaft is the key success factor for suppliers. Optimal functional distribution of the involved components ensures ideal interaction, performance, packaging, and cost. System efficiency gains can offset high costs for the overall EV battery (e.g., a 1 percent efficiency gain saves about USD 150 in battery costs). Building on this competence, successful e-drive suppliers can focus on the optimization of power density on a system level. Finally, the development of dedicated and integrated cooling cycles will help achieve further cost advantages.

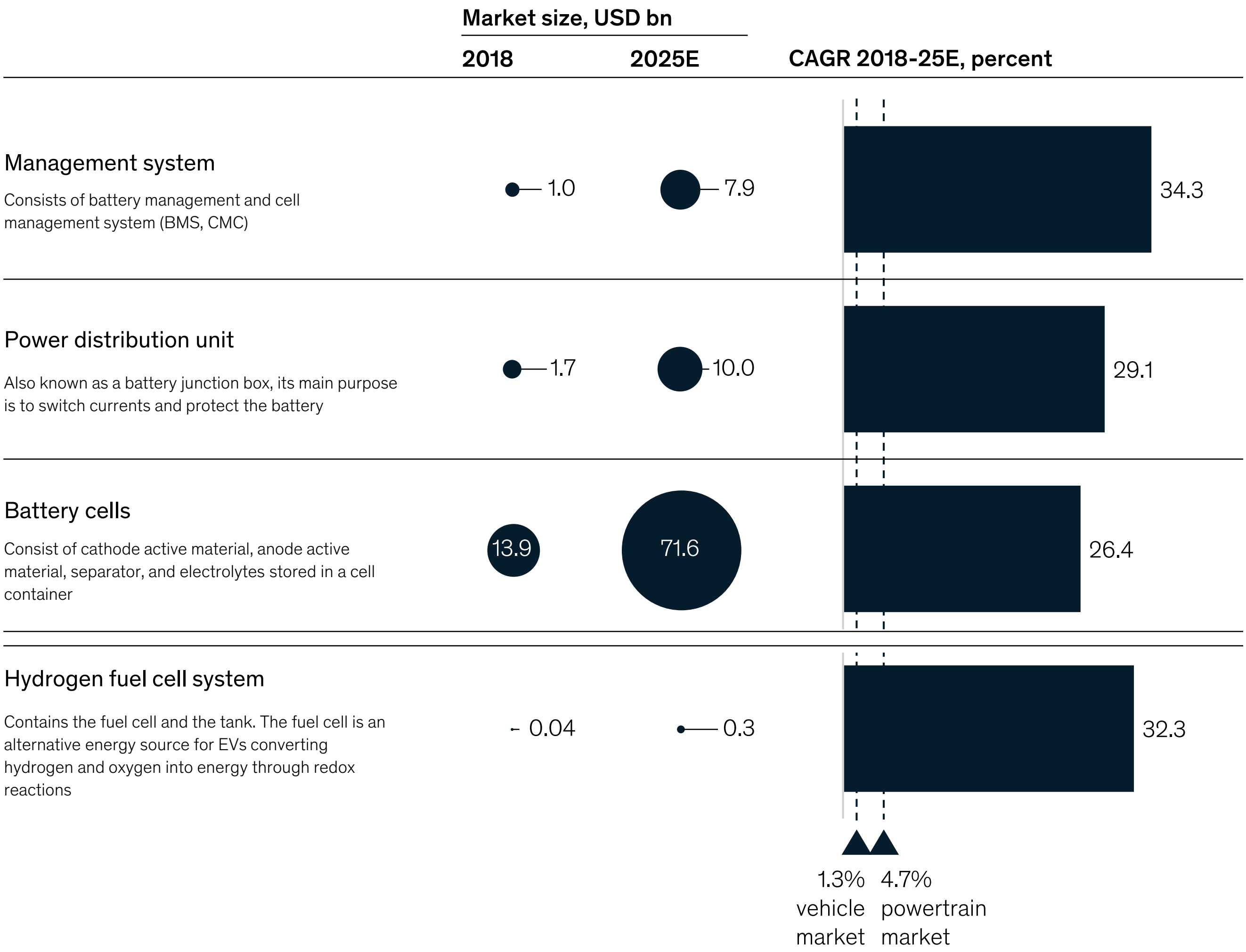
— *Software competence.* Suppliers of e-drives will want to increase focus on system integration via software development (ECUs, TCUs, PDCUs). Controlling software can be developed by service providers, yet internal know-how is beneficial; once basic software is created, it can be customized for different OEMs. From a performance perspective, building software expertise will further allow e-drive suppliers to optimize the interplay between different parts of the EV via a control unit. Big data competence will enable e-drive suppliers to increase efficiency of the e-drive under varying operating conditions. Furthermore, it may allow suppliers to apply machine learning to reduce failure rates, anticipate maintenance needs, and improve the lifetime cost of the electric powertrain.

2.5 Battery pack – innovation and large-scale industrialization

Market assessment (Exhibit 12)

Exhibit 12

Market assessment of battery pack and hydrogen fuel cell system



Source: McKinsey Center for Future Mobility

At the heart of electrification is the battery, whether as a sole power source (as in BEVs) or in combination with other power sources, such as fuel or hydrogen. In current BEVs, the battery pack represents around 50 percent of the total costs. Usually, the battery pack consists of the following components:

— *Battery cells.* These cells contain the energy from charging and discharging, consist of cathode active material (determines battery voltage capacity), anode active material, separator (prevents short-circuiting), and electrolytes (balance current flow) stored in a cell container.

— *Battery module.* The battery cells are connected within a frame forming a "module" to protect them from external shocks, heat, and vibration. This format allows for different battery architectures with cells connected in a series or in parallel to increase either the voltage or current output.

— *Management controllers (MCs).* MCs come in different layers, namely cell management controllers (CMC) and module management controllers (MMCs). CMCs are directly mounted on the battery cells to measure cell voltage and temperature and communicate via digital two-wire buses. MMCs collect the information of several CMCs and carry out data processing.

— *Battery management system (BMS).* A BMS is an electronic control board, which is the interface between the battery and the VCU. Its main purpose is to use charge and load leveling to prevent damage to the battery pack that can come from deep discharge, overvoltage, fast discharging, and high current drain. The BMS also collects information from the MCs to monitor various cell parameters (e.g., cell voltage, temperature, current flow, number of charge/discharge cycles), calculate the battery's state of charge/operating time, and determine battery health. The degree of system complexity scales with the number of cells in the pack, which presents a disadvantage for cylindrical cells.

— *Power distribution module (PDM).* Also known as the battery junction box (BJB), the PDM is a switch that connects/disconnects the battery from the power electronics. Its main purpose is to route high currents and protect the battery from overcurrent via safety fuses, switches, (pyro) switches, resistors, breakers, relays/contactors, electrical connections, and solid-state power controllers (SSPCs).

— *Cooling system.* Temperature control of cells is important for the safety, functionality (cold start), and performance of a battery pack. Cooling systems can be grouped into passive and active cooling systems and use either air or liquids as a coolant. Fully immersing the battery cells into a coolant is a technique used for the highest-performance applications.

Market size and growth

Globally, EV battery cell supply is projected to grow to approximately 750 GWh by 2025 – an annual increase of 20 percent from about 200 GWh in 2018. While this matches the demand until 2023, supply shortages might occur in the period afterwards if additional capacity is not rapidly scaled up. For Europe, supply is projected to grow annually by approximately 40 percent from about 15 GWh in 2018 to more than 150 GWh in 2025, just about matching the forecasted demand. In Europe, this may lead to supply shortages if either demand rises faster than expected or if it takes more time to reach full utilization of planned capacities (Exhibit 13). Production capacity increase in Europe is mainly driven by Asian battery suppliers building large plants near European OEMs as well as by Northvolt, which is building a 32 GWh factory in Sweden.

Economies of scale and technology improvements, such as high-energy cathodes with lower cobalt content by 2025 and solid-state electrolytes by 2030, will lead to lower costs, further driving the uptake of xEVs.

Our proprietary McKinsey battery cost model analyzes the key drivers of battery costs on a factory level and matches these drivers with our view of current and expected supply capacity. Hence, the model has a built-in cost curve of single plants and can differentiate costs for average and best-in-class producers.

To model the costs, factors such as raw material prices, active material assembly costs, labor costs, energy prices, location (including productivity), age, size of the plant, SG&A, shipping, import costs, yield, profit, and pack component prices are taken into consideration. This bottom-up approach leads to a detailed forecast of different component costs, such as battery cell components (with further breakdowns for cathodes anodes, etc.) or cell assembly (including labor or energy costs).

Based on this detailed cost breakdown, we have created two battery cost scenarios that are based on distinct market development projections. In the base case, we assumed a lower demand for batteries combined with reduced learning rates and slower technology developments (e.g., introduction of advanced NMC811 cells). The breakthrough case, on the other hand, is based on quicker battery demand development accompanied by higher learning rates, faster technology development, and stronger profit reduction. In our mid-2019 update of the battery cost model, these assumptions led to average cell costs of USD 135/kWh in 2019 and USD 85 to 95/kWh in 2025. Raw materials will make up around 65 percent of the total cell cost in an optimal production process in 2025.

Industry structure

Asian battery producers have been dominating the battery market and lead technology development. Early efforts by incumbent European and North American OEMs to manufacture cells in-house were not successful. Currently, the following OEM-supplier relationship models can be observed:

— *OEM-integrated model (high involvement of automotive OEM).* OEMs work in a joint venture with battery manufacturers.

— *OEM-packaging model.* OEMs take over manufacturing of module and battery packs; cells are externally sourced.

— *OEM-directed model.* OEMs work with tier-1 suppliers that integrate cells, BMS, and other components, but OEMs retain tight control over the design, engineering, and selection of subsuppliers.

— *OEM-outsourced model (low involvement of automotive OEM).* OEMs that lack battery/ xEV expertise purchase the full pack from suppliers.

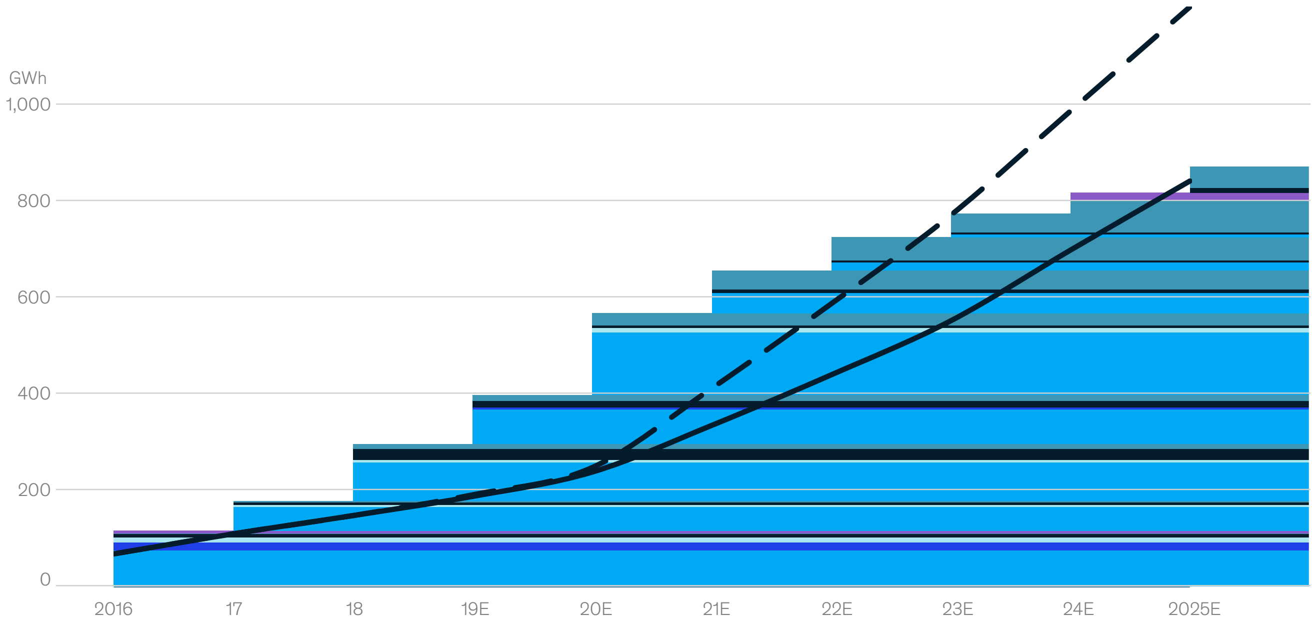
Exhibit 13

Outlook on global and European battery demand and supply – temporary supply shortages possible in Europe

Global EV LiB cell supply (based on announcements) and expected demand, GWh

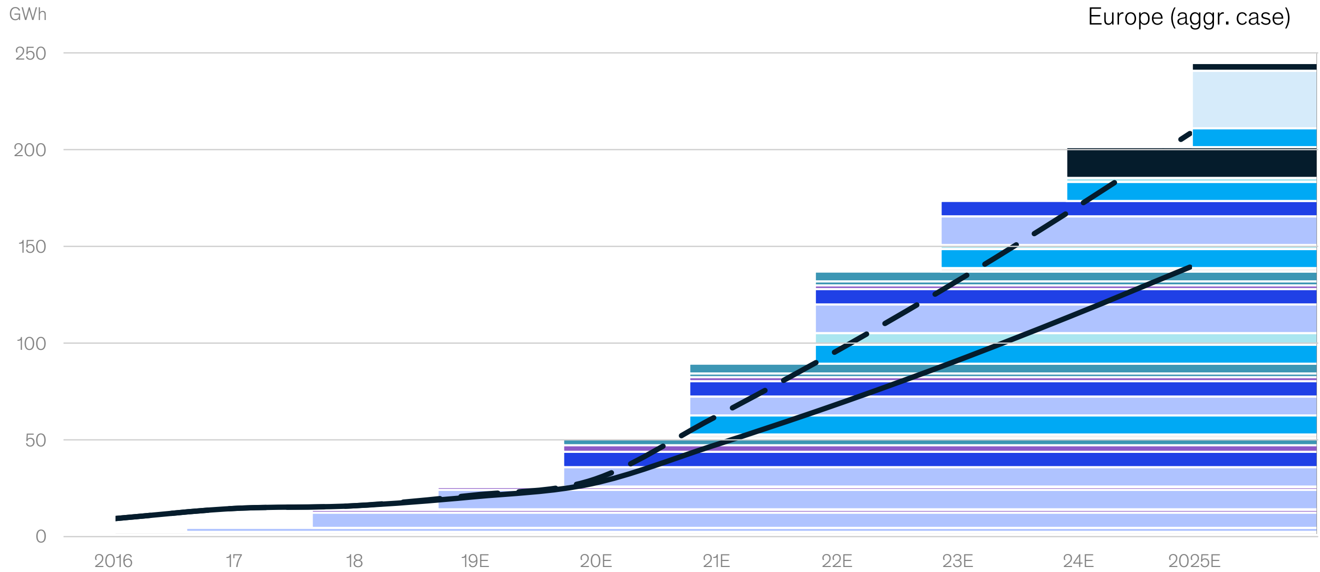
China | Japan | South Korea | North America | Europe | RoW

Battery demand (base case) | Battery demand (aggressive case)



European EV LiB cell supply (based on announcements) and expected demand, GWh

- 20 GWh Germany, Salzgitter
- 32 GWh Norway, Skellefteå
- 50 GWh[1] Germany, Erfurt
- 10 GWh Germany, Bitterfeld-Wolfen
- 18 GWh Hungary, Komárom
- 11 GWh Hungary, Göd
- 70 GWh Poland, Wroclaw
- 30 GWh Germany, Emscher-Lippe
- ~7 GWh Others
- Battery demand Europe (base case)
- Battery demand Europe (aggr. case)



1 CATL aims for 60 GWh by 2026, Volkswagen/Northvolt for 24 GWh by 2026 or somewhat later

Source: McKinsey Center for Future Mobility, September 2019

Further upstream, in battery cell production, Asian players currently provide across all components between approximately half to three-quarters of the market and an operating profit between 8 and 14 percent, despite increasing competition.

Key (technological) trends

In the following, key technology trends are described along the core elements of a battery:

— *Cathodes.* Previous cathode chemistry focused on relatively safe technologies such as LFP (lithium iron phosphate) or LMO (lithium manganese oxide), but due to their restrictions in energy density, this has already shifted towards mostly nickel-based materials, in particular NCA (lithium nickel cobalt aluminum oxide) and NMC (lithium nickel manganese cobalt oxide). We foresee current NMC532 and NMC622 being replaced over the next three to five years by higher-energy density cathodes such as NMC811. While nickel generally increases the energy density of a battery, cobalt is used to stabilize the system. The transition to higher nickel content is enabled by higher homogeneity and purity of the cathode active material and advanced battery cell management of thermal stability.

— *Anodes.* Today, the dominant anode material for xEV applications is graphite. Its key advantages include its similar potential to lithium, enabling a high cell potential and, thus, energy of the battery, low costs, an easy manufacturing process, safety, and environmental friendliness. To increase the anode energy density, silicon is added in small amounts (approximately 5 percent). The additive amount is expected to rise to up to 20 percent until 2025, resulting in a three times higher energy density of approximately 1,000 mAh/g.

— *Electrolytes.* The development of next-generation electrolytes focuses on the improvement of liquid electrolytes and the introduction of solid electrolytes. Liquid electrolytes face key challenges with safety issues due to high flammability and toxicity and limited stability, which currently prohibit the use of HV cathode materials for an energy density increase. A number of additives to tackle these challenges are under development, with some likely to come to market over the next few years. One of the most discussed technologies are solid-state battery cells, which differ from current cell technology in that they use solid electrolytes rather than liquid electrolytes. Solid electrolytes have the most disruptive potential regarding energy density, safety, temperature stability, and costs. These can lead to a significant decrease in charging times, which is a game changer for EVs. These shorter charging times lessen the need for long-distance range, also enabling the use of smaller batteries. Their development and timeline to commercialization, however, are still uncertain, and scaling before 2025 is unlikely. Several materials (e.g., polymers, sulfides, oxides, phosphates) are summarized under the term “solid state,” each with specific advantages and disadvantages. Currently, the most promising technology is sulfides, which allow for high current densities (i.e., fast charging), stability at elevated temperatures (i.e., they require a smaller cooling system), and good manufacturability. Another advantage of solid electrolytes is their potential to allow a stacked cell design using bipolar electrodes. In combination with a cooling system, this could significantly reduce weight, volume, and costs of battery packs. However, the biggest challenge for this material class is its vulnerability to water, which requires production under inert gas.

— *Battery pack voltage is increasing from an average of 400 to 800V.* This will improve charging speed. It also results in less costs as lower current density leads to reduced size of busbars and cables.

— *Other components are expected to see incremental developments.* Management controllers will benefit from reduced cost and better efficiency through multilayering. An increased modularity of the battery management system will likely lower costs and enable more precise measurement and thus a higher system performance (e.g., faster charging). The power distribution module can be improved in certain areas by using more compact geometries and optimized material use (copper versus aluminum, mechanical relays versus semiconductors), which will extend lifetime due to lower risk of overheating and elimination of mechanical components. Battery chargers will allow for faster charging speed through higher voltages and temperature resistance when silicon carbide replaces silicon in metal-oxide-semiconductor field-effect transistors (MOSFETs).

Success factors for suppliers

Several factors will be essential to suppliers' success in battery cell production:

— *Technology leadership.* Suppliers need to stay on top of the rapid changes in battery technology by both internally innovating and cooperating with pioneers along the value chain. New alliances between OEMs, cell manufacturers, and producers of cathodes, anodes, separators, electrolytes, and specialized materials are emerging.

— *Cost competitiveness through scale.* For battery manufacturing, one main driver to achieve cost competitiveness is scale, which results in less capex per unit produced as well as lower SG&A and R&D costs. Increased purchasing power helps to secure supply and improves the negotiation position downstream.

— *Access to raw materials/supplier agreements.* The most critical raw materials will be cobalt and nickel, which are typically acquired by the company producing the active material for the cell manufacturer. Picking the right partners, or even vertically integrating upstream, could be increasingly important to mitigate impacts from supply chain bottlenecks.

— *Automotive-grade quality.* In contrast to consumer electronics – the origin of today's lithium-ion batteries – the batteries for vehicle applications must be of automotive-grade quality. This means a failure rate of only a few per million and reliability under harsh environmental conditions.

— *Proximity to OEMs.* This trend goes in the direction of close cooperation between battery suppliers and OEMs that are likely to purchase the cells from selected suppliers and package them in-house. This requires proximity to OEMs in order to secure relevant offtake volumes and to quickly adapt to changing requirements. Additionally, this proximity is needed for suppliers in order to allow them to offer complete 48V systems (e.g., including key auxiliaries in the portfolio) requested by OEMs, especially in China.

— *Circular economy and sustainability.* The sustainability image of battery manufacturing is coming under increasing scrutiny, and proposals for lifecycle assessment of batteries, labeling, and environmental standards for the industry are being discussed by policymakers. At the same time, OEMs are looking for ways to both avoid recycling costs from batteries and recover valuable raw materials. Innovations in product design, recycling technology, and even new circular business models could be promising avenues for cell makers and suppliers.

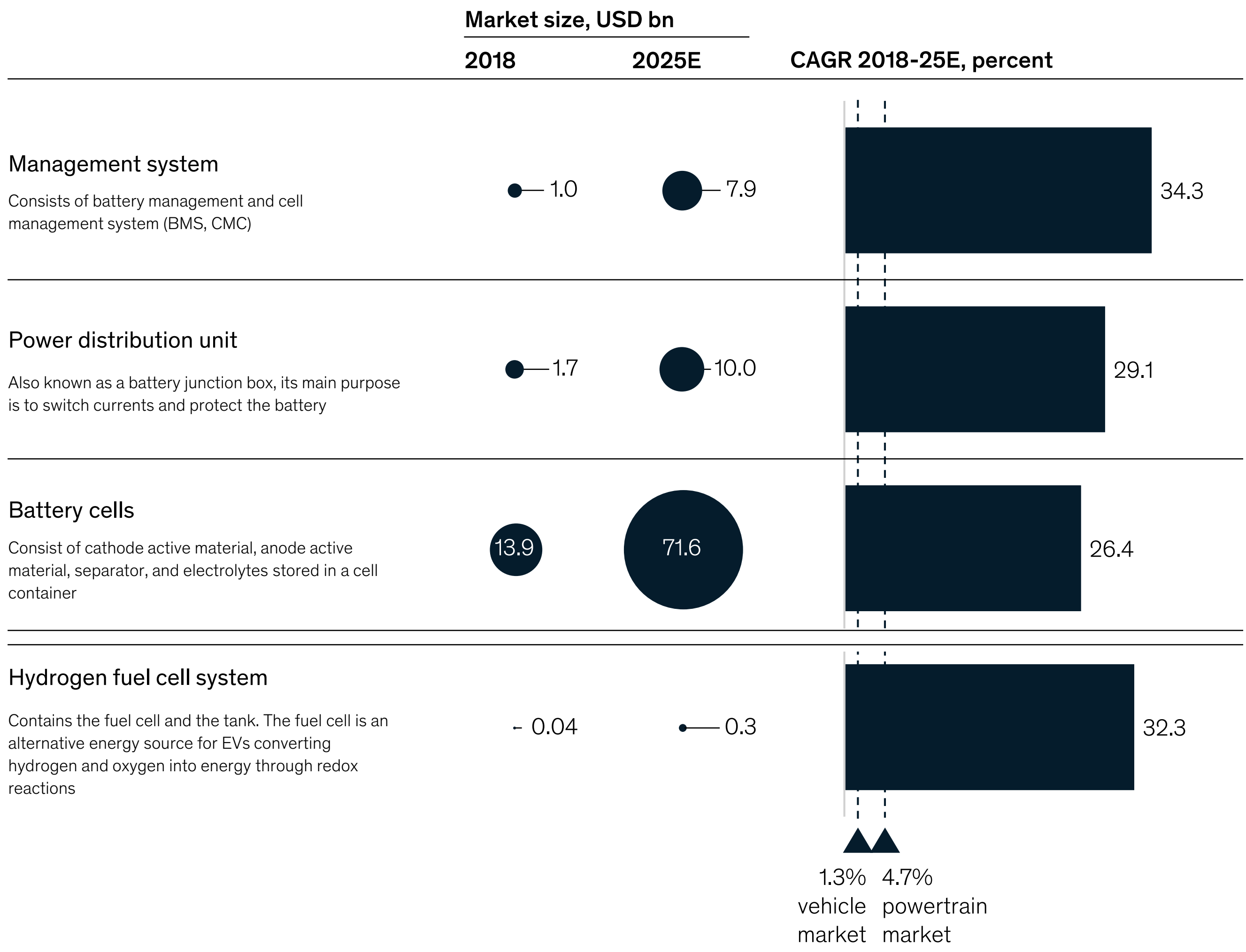
— *Value chain transparency.* The rapid scale-up of the battery value chain (by a factor of 14 times by 2030) implies fast-growing demand for certain critical raw materials and entails several environmental and social risks (e.g., child labor in cobalt mines). Suppliers with enhanced transparency and compliance standards vis-à-vis those risks will have a better selling proposition, especially Western OEMs.

The World Economic Forum and the Global Battery Alliance has just published the report "A vision for a sustainable battery value chain in 2030," which analyzes a pathway to capture the full economic potential of batteries and outlines its most effective possible contribution to sustainable development and climate change mitigation.

2.6 Hydrogen fuel cell system – testing for application at scale and managing investment

Exhibit 12

Market assessment of battery pack and hydrogen fuel cell system



Source: McKinsey Center for Future Mobility

Market assessment (Exhibit 12)

Hydrogen and fuel cell systems are an alternative power storage to batteries and can be used in vehicles as well as in stationary applications. FCEVs offer several advantages that could make them attractive, in particular, for vehicles with higher weight and longer ranges:

— Hydrogen refueling is comparable to petrol refueling, offering the convenience and high uptimes of ICEs.

— Fuel cell systems are scalable to heavy vehicles without major increases in battery size and weight.

— Small hydrogen tanks and fuel cell stacks can also be used as range extenders for EVs.

Hydrogen and fuel cell systems consist of three main subcomponents:

— *Hydrogen storage tanks.* Compressed gaseous hydrogen is stored in a hydrogen tank onboard. The standard pressure is 70 MPA/700 bar. Hydrogen tanks for automotive applications are made from several layers:[9] a load-bearing aluminum alloy tank lined with plastics on the inside and one or two protective external layers made from composite materials (e.g., carbon fiber reinforced polymers, continuous glass fiber composites).

— *Fuel cells.* Fuel cells convert hydrogen to electricity by combining hydrogen with oxygen, generating water as the only by-product. The most common type of fuel cell used for automotive applications are proton-exchange membrane (PEM) fuel cells. A single fuel cell supplies an open circuit voltage of 1V; many fuel cells are combined in a fuel cell stack to achieve the required voltage. A fuel cell consists of the following elements:[10] a polymer electrolyte membrane at the center of the fuel cell prevents the direct reaction of hydrogen and oxygen but allows protons to pass through it; the polymer electrolyte membrane is hot-pressed between two catalyst layers, which are in turn hot-pressed between carbon electrodes on the anode and cathode side of the fuel cell. Most PEM fuel cells use platinum catalysts. Despite the massive reductions in the amount of platinum used per cell, platinum still constitutes almost half the costs of a single fuel cell; graphite flow field plates distribute hydrogen and oxygen across the active area of the fuel cell and support water and temperature management. Copper current collector plates draw the current away from the fuel cell and towards the e-motor. Aluminum end plates hold the fuel cell together.

— *Small battery.* A small battery (1 to 2 kWh) is used to store excess energy and provide additional power when needed (Chapter 2.5, Battery pack).

Market size and growth
FCEVs are still a rare sight on the streets, with only five models on the market and approximately 4,000 vehicles sold worldwide in 2018. However, 14 OEMs have announced that a total of 22 models will reach the market by 2025 (compared to approximately 300 BEV models by 2025). In addition to the expected trend in FCEV passenger cars, there has been recent momentum in the development of FCEV duty vehicles, with major manufacturers and new market entrants launching fuel cell trucks. Because commercial fleets (for cars and trucks) require less refueling station coverage than private cars, they are most likely to be early adopters of FCEV technologies.

In terms of component revenue, about 50 percent will be generated by the fuel cell itself, and the other 50 percent will come from the tank and other auxiliaries.[11]

Industry structure
Large chemical and material companies lead the production of components such as membranes, electrodes, catalysts, MEAs, and bipolar plates. Fuel cells and stacks are assembled by companies, including tier-1 suppliers and specialized players. Some OEMs assemble their own fuel cell systems and integrate them with the powertrain.

[9] Hanane Dagdougui, Roberto Sacile, Chiara Bersani, Ahmed Ouammi (2018): Hydrogen Infrastructure for Energy Applications: Production, Storage, Distribution and Safety (https://doi.org/10.1016/B978-0-12-812036-1.00004-4).
[10] Karthikeyan Karuppanan, Manoj Panthalingal, Pullithadathil Biji (2018): Nanoscale, Catalyst Support Materials for Proton-Exchange Membrane Fuel Cells; In: Chaudhery Mustansar Hussain, Handbook of Nanomaterials for Industrial Applications (https://doi.org/10.1016/B978-0-12-813351-4.00027-4).
[11] Fuel cell stack and housing, hydrogen storage tank and pipes, fuel cell ECU, humidifier, air compressor, actuators (valves, pressure regulator), sensors (temperature, current, voltage). Note: thermal management not included

Key (technology) trends

Several recent technological developments are shaping the next generation of fuel cells:

- *Reduction of platinum content.* Since 2005, approximately 80 percent less platinum has been used in fuel cells, resulting in a significant cost reduction.

- *Modularization of fuel cell stacks.* Modular design enables meeting power grade requirements of various transport applications and reduces costs through manufacturing efficiency.

- *Durability and lifetime.* Fuel cells have also achieved important gains in durability and lifetime through better thermal stability.

- *Automation in manufacturing.* Going forward, scale-up of production and automation is the largest potential cost reduction lever if production goes from a few units to mass production. The US Department of Energy projects that the production cost of a PEM fuel cell system (for MDV) can decrease from more than USD 100 to 150/kW to roughly USD 45/kW with today's technology if production were scaled up from less than 1,000 to 500,000 systems made per year. TCO parity of FCEVs with ICE depends on the scale-up of the hydrogen infrastructure and the cost of producing clean hydrogen. We see TCO parity of fuel cell versus ICE in the late 2020s.

Success factors for suppliers

Suppliers positioning themselves for success in the FCEV market can look to the following indicators:

- *Modular fuel cell stack systems.* Modularizing fuel cell stack systems will help suppliers meet the range of power needs of FCEVs.

- *Integrated system.* A system in which power electronics, batteries, and controllers are integrated is the basis for optimizing FCEV's range, driving performance, cost, and efficiency.

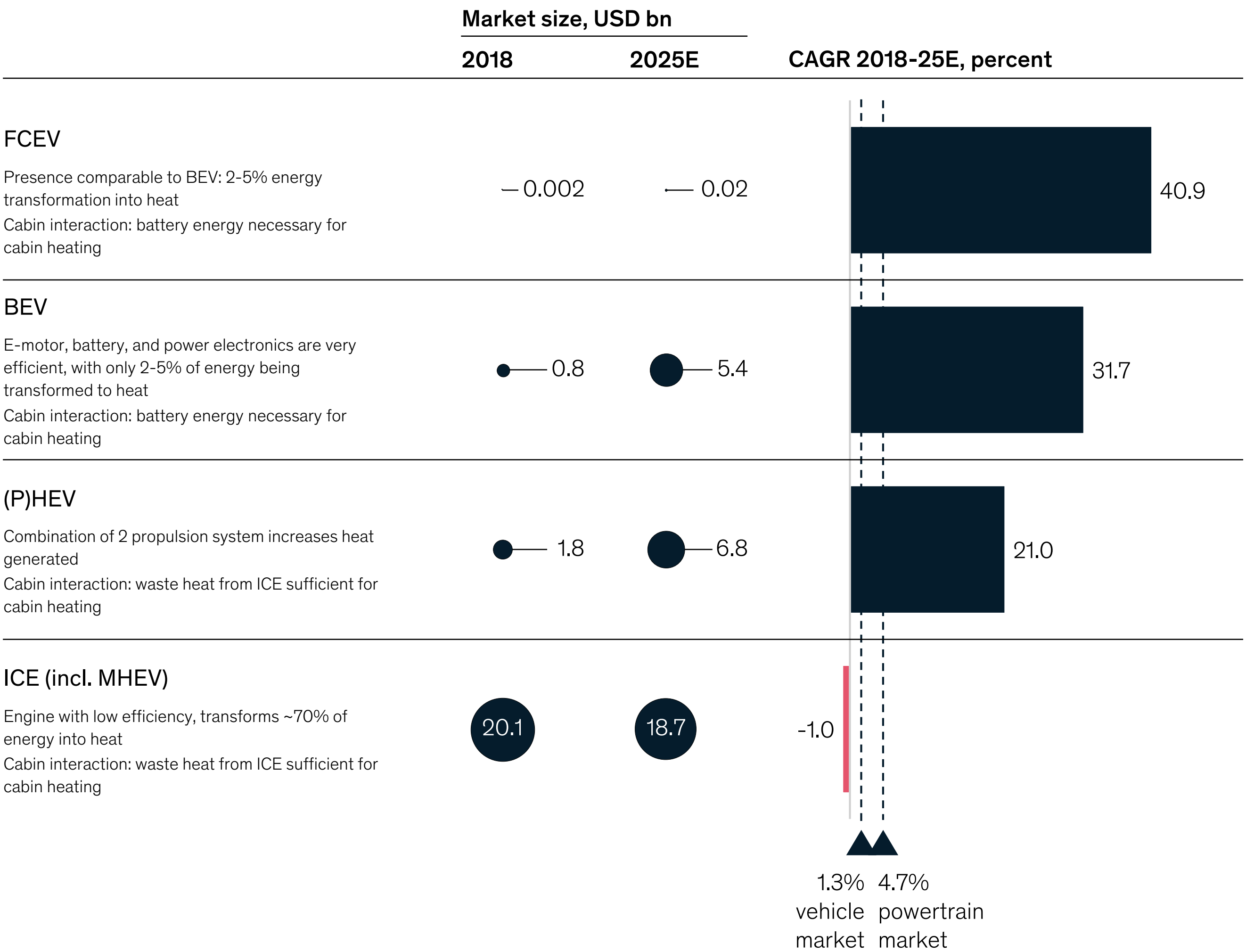
- *R&D partner network.* A network focused on innovation can facilitate the integration of new developments in components (e.g., in bipolar plates and membranes) into manufacturing. In general, the FCEV market has the potential to grow strongly in the long-term future. Given the uncertainty around the timing of the expected market uptick, however, there is an advantage for individual suppliers to identify a network of partners in order to mitigate risk.

2.7 Thermal management – drive towards unification in one system

Market assessment (Exhibit 14)

Exhibit 14

Market assessment of the thermal management system



Source: McKinsey Center for Future Mobility

Market size and growth
Growth of thermal management systems in terms of content per vehicle is driven by more complex thermal management architectures for electric and hybrid vehicles. For the application of thermal management to ICE vehicles, we expect standard long-term-agreement price decreases roughly matching productivity gains. In full and plug-in HEVs, we expect a rise in price for thermal management due to the increasing shift from mechanical to electrically powered components. For fully electrified vehicles, i.e., FCEVs and BEVs, we expect higher prices due to more noise-reduction and additional cooling requirements due to a shift to fast charging. We also expect intelligent thermal management systems to increase range.

Industry structure
Thermal management is provided both by OEMs and suppliers, with OEMs handling the system integration and suppliers predominantly supplying subsystem components, e.g., pumps and valves. In the thermal management market, the top four suppliers account for about two-thirds of the total revenue.

Key trends
Several recent technological developments are shaping the next generation of thermal management components:

— *48V-enabled thermal management.* Due to the increasing electrification of vehicles (from MHEVs to BEVs), we see new technologies emerging: first, the availability of 48V power supply will lead to the deployment of more electric-powered thermal management components. These elements will be more efficient, better performing, and consuming less energy than conventional mechanical or 12V-enabled parts. Second, quieter vehicles from electrification raises the requirements for mechanical components (e.g., pumps, ventilators) to also be quieter. This can be achieved either via increased noise insulation or via optimized design of the complete thermal management system.

— *Higher thermal resistance.* Two technology trends will raise the thermal resistance of thermal management components. First, the shift in semiconductors in power electronics from silicon oxide (SiO) to silicon carbide (SiC) will lead to less heat loss from power electronics and thus reduced cooling requirements. This, in turn, will allow for an increased current density, which will support faster charging. Second, beyond 2030, the semiconductor battery trend will allow for a decrease in cooling since they operate at temperatures of -20°C to 100°C (Chapter 2.5, Key trends).

— *System integration.* A general shift to optimized design of secondary motors for pumps and auxiliary systems within the thermal management and system integration of the coolant circuits in the vehicle will lead to a performance and efficiency increase.

Success factors for suppliers
Since thermal management is becoming more complex and differentiating in HEVs (combination of two thermal management cycles) and BEVs (key influencer of efficiency, range, and battery lifetime), superior system understanding is key to the success for suppliers.

Specifically, suppliers with the ability to transfer knowledge from classical thermal management systems to the more complex hybrid thermal management systems will have a significant advantage. A comprehensive system understanding of thermal management for ICEs and xEVs can lead to superior robustness and coolant flow control, thus improving vehicle range.

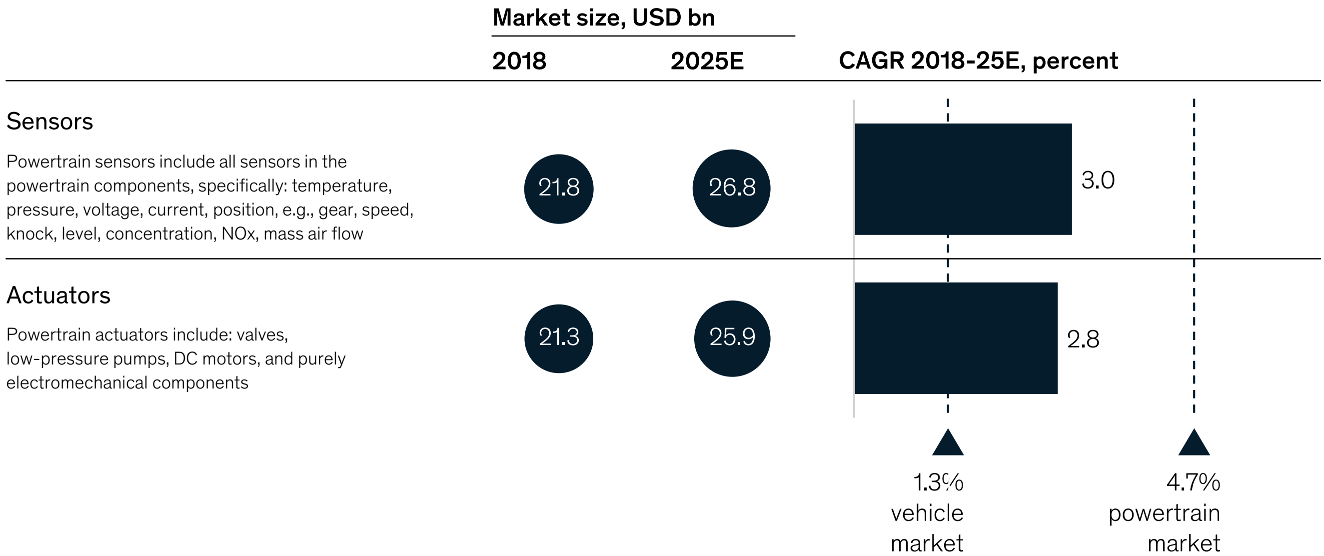
2.8 Sensors and actuators – increased importance for powertrains

Due to the special context of these components, we will deviate in this section from the structure applied for other components and refrain from discussing industry structure.

Market assessment (Exhibit 15)

Exhibit 15

Sensor and actuator market, global revenue development



Source: McKinsey Center for Future Mobility

Sensors and actuators are key elements of the powertrain responsible for the controlling and functioning of all components. We defined the sensor market as comprised of all sensors in the powertrain related to temperature, pressure, electrochemical sensors (e.g., NOx, O2, lambda), speed/position (e.g., rotational speed, camshaft position, crankshaft position, gear position), power sensors (e.g., voltage, current), and other sensors, such as those monitoring mass air flow, fluid levels (e.g., oil and fuel), and knock sensors.

The actuator market includes, in principle, elements that convert an electronic signal from the control unit into a mechanical or hydraulic action. In this report, we focus on valves, low-pressure pumps, and the DC motor that make up the actuator market. Competence in sensors and actuators requires system understanding along with electronics and software know-how.

Market size and growth
While the sensor and actuator market are both growing at higher speed than the underlying vehicle market, they are expanding more slowly than the powertrain market.

The sensor market development is influenced by two contrary effects. On the one hand, large parts of the powertrain do not include sensors at all, but this is changing. Electrification of the powertrain, improvements in performance, e.g., optimized fuel consumption and increased emission regulations in the context of real driving emissions (RDE), are leading to faster growth in the powertrain market for NOx, temperature, and pressure sensors in the aftertreatment system. Sensors are necessary for fine-tuning the system and advancing any aspects in performance, fuel consumption, and/or emissions.

On the other hand, the actual number of sensors in certain areas of the powertrain is decreasing, as sensors are being replaced by computational power and vehicle performance/status increasingly predicted by the control units of the vehicle. In addition, there will be fewer sensors in electric powertrains than in conventional powertrains.

The actuator side is largely influenced by the transition from a 12V to an above-48V power supply and becoming more and more electrified as well as optimized for higher system voltages. In addition, the key requirements for actuators in terms of emission regulations and electrification are energy efficiency and noise limitation (due to the quietness of e-motors).

Key trends

— *Higher number of sensors with increased technological requirements.* There will be more sensors applied to performance, fuel consumption, and emissions, e.g., in the area of RDE, and more related to the electrified powertrain, e.g., in the cell module controller for battery cells. Higher pressure (injection system) and increased system voltage also mean more requirements for sensors. At the same time, standard sensors will likely witness greater commoditization with no additional significant technology development expected.

— *Higher numbers of actuators in transmission systems.* In transmissions, we see a shift from manual to more automated transmissions. This is due to more efficiency requirements and electrification of vehicles and will increase the overall number of actuators.

— *Increase in the electrification of actuators will follow a rise in the electrification of vehicles.* Advanced sensors also boost the demand for more precise actuators. Finally, lower construction/process tolerances require higher-tech actuator solutions, especially for engine, turbocharger, and aftertreatment systems.

Success factors

Knowledge on embedding critical sensors and actuators into the powertrain based on overall system understanding is an important factor for ensuring performance efficiency, low fuel consumption, and emissions. Sensors and actuators are key components in this context, as discussed in Chapter 2.3. Additionally, extensive technological expertise is required to ensure the optimal production or sourcing of adequate sensors and actuators.

3 Outlook

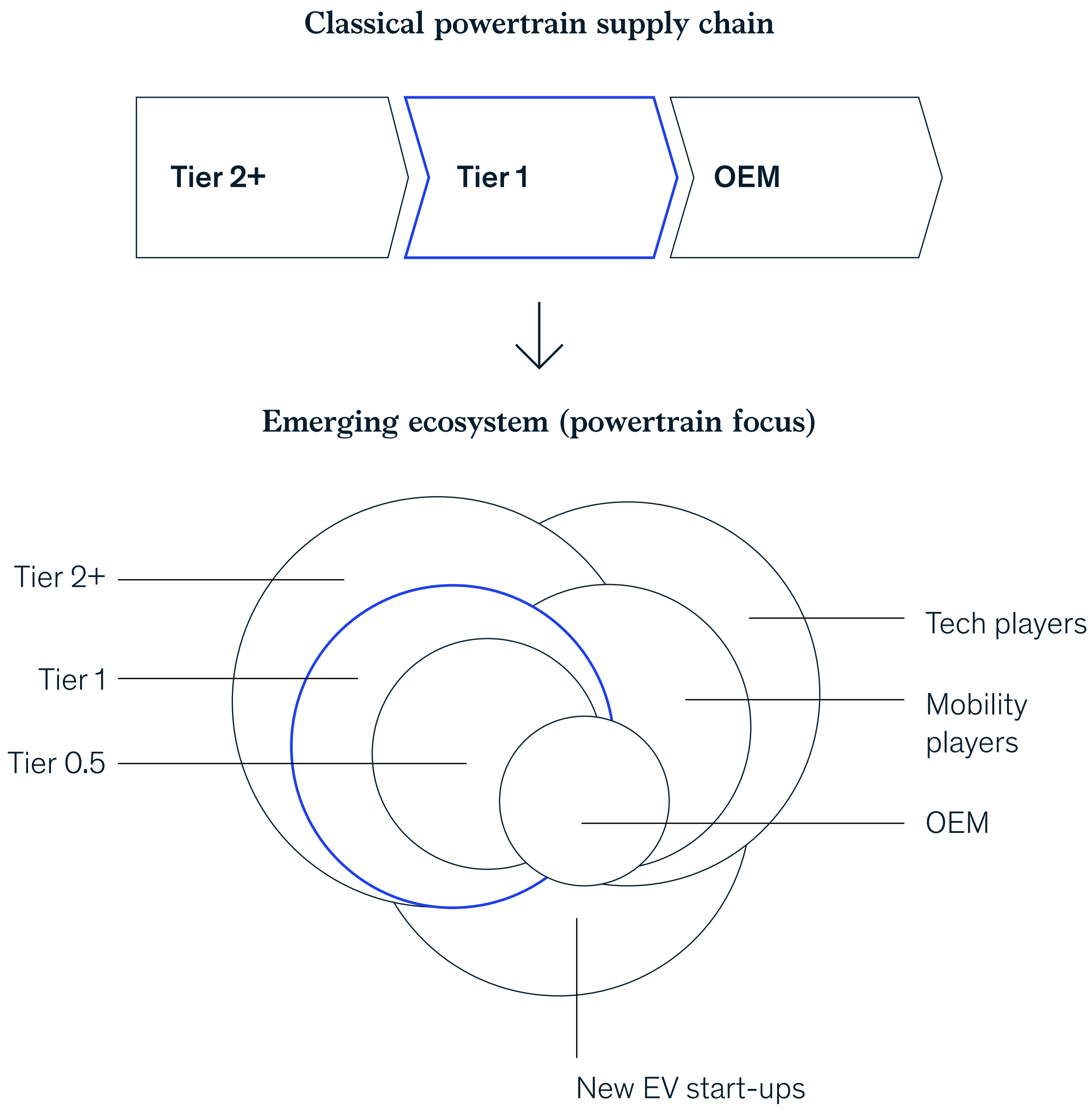
The transformation of the powertrain value chain – and how to master its strategic challenges

3.1 Disruptions ahead in the traditional powertrain value chain

E-mobility is at a tipping point: increased CO_2 regulations, a shift in consumer preferences to clean transport solutions, declining battery costs, and growing availability of required infrastructure will accelerate the rollout of EVs across major markets in the early 2020s. The scale and scope of these trends is currently disrupting the supply chain (Exhibit 16).

Exhibit 16

Vehicle electrification is disrupting the powertrain supply chain – tier-1 suppliers are under increased pressure from up- and downstream competition



Source: McKinsey Center for Future Mobility

Over the past decades, a linear supply chain from tier-2+ suppliers to tier 1s and OEMs has been predominant in the automotive industry. Now, due to electrification (and other technological trends), the supply chain is evolving into an ecosystem with fluid industry boundaries. Tier 1s are redefining their portfolios and, in some cases, moving downstream towards tier 0.5 status by offering integrated electric chassis solutions. Meanwhile, tier 2s and non-automotive suppliers (e.g., semiconductor, battery, and electronics players) are looking for opportunities in the e-mobility industry. These disruptive industry forces are impacting the classical OEM business model, causing automakers to redefine the extent to which they vertically integrate their electric powertrain production. When doing so, they must choose one of three fundamentally different make-buy strategies: complete outsourcing of the electric powertrain (the choice of EV start-ups and many Chinese OEMs), purchasing components and integrating them in-house, or a high degree of vertical integration.

The OEM's play in the powertrain supply chain will likely change substantially. The conventional ICE powertrain components have an established, globally interlinked supplier landscape. Despite base engine and transmission for parts of the market, ICE powertrain components are produced by suppliers and in some cases co-developed (e.g., turbochargers). The supply chain for electric powertrains is currently evolving. We expect that electro-mechanical components, such as e-motors and e-drives, will eventually be insourced by some OEMs (approximately less than half of the market), with power electronics potentially remaining a supplier market. Regarding batteries, packaging will likely remain an OEM play as cells are predominantly supplied by battery producers. The battery management system will be mostly be provided by suppliers, and application software will be controlled by OEMs.

These strategic shifts among industry players are putting increasing pressure on existing and emerging tier-1 supplier markets. As of today, for example, there are over 20 different suppliers for e-motors, and the resulting market environment is highly competitive and complex. Limited market size, narrow OEM margins on EVs, and high competition make for a challenging market. Large investment is required, compounding the economic challenge. We expect the value chain to balance out over the next five to seven years when CO_2 regulation enforcement and potential penalties will define a clear roadmap for EVs in major markets. In other words, the market is likely to consolidate with five to ten electric powertrain suppliers. A focused powertrain transition strategy is therefore essential to being successful in a highly competitive and complex environment.

Beyond a sound strategy, mastering the transition to electric powertrains also requires new skills. The ability to develop and produce electric powertrain components depends on a shift in capabilities from thermodynamic and mechanical engineering skills alone to electromechanical engineering, electrics/electronics, and semiconductors. In order to fill competence gaps, suppliers and OEMs are currently joining forces. More than 30 different partnerships of various forms (including not only conventional partnerships, but M&As and JVs) have been formed over the last five years for both LV and HV e-drives.

In this new electric powertrain industry, suppliers will have two fundamental paths for differentiating themselves: they can excel at system design and optimization and/or use economies of scale and modularity to be cost competitive.

Excelling at system design and optimization means understanding the interplay of electric-to-mechanical-power conversion (and vice versa), electric powertrain stabilization, and vehicle thermal management, under varying operating conditions and translating performance requirements into component specifications. Because some suppliers lack design-to-value capabilities, overspecification is a common problem in first-generation e-drives and power electronics. Suppliers that can draw on a high level of software and electronics skills will be more likely to develop system solutions that meet the performance requirements of electric driving.

Another aspect of system understanding is the ability to bring software excellence to the next level. An ideal powertrain includes sensors that precisely measure physical parameters, control units, and software algorithms that make smart decisions and system-optimized functional components that actuate the powertrain hydraulically, mechanically, or electronically. Suppliers that combine these capabilities can more easily develop differentiating products and position themselves as preferred suppliers for OEMs and new EV start-ups. System understanding of a vehicle and assembly level further enable suppliers to develop products that can be efficiently put together and integrated into the vehicle on OEM production and assembly lines.

Cost excellence will also be crucial for electric powertrains, where performance – measured in kW – is less differentiating than for combustion engines. A clear cost focus is essential for a healthy supplier business model. Such a model should comprise lean high-yield manufacturing processes on a large scale, purchasing cost optimization through relevant volume for critical raw materials and components (e.g., rare-earth elements for e-motors, semiconductors), and modular design to reduce development costs while offering e-drives at different performance levels.

Powertrain suppliers should focus on expanding the category of capabilities that represents a barrier to entry for suppliers from other industries: their powertrain system comprehension and understanding. Doing so puts them in a favorable position with existing and new OEMs. Incumbent suppliers that use their system understanding to complement their powertrain know-how with electronics capabilities could become the partners of choice for optimized components and subsystems for HEVs. Furthermore, building on their system expertise, incumbent suppliers could quickly develop improved e-drive systems that become state-of-the-art solutions for existing and new EV players.

3.2 Portfolio challenge – which powertrain component clusters offer superior value generation opportunities

Based on our understanding of the competitive dynamics at play (Chapter 3.1) and the outlook for powertrain electrification (Chapters 1 and 2), we have identified which market segments have the potential to generate above-average value. Exhibit 17 shows how we rated powertrain component markets in terms of their differentiation potential and market attractiveness. While they will differ on an individual supplier level, we expect the overall picture and key messages to remain largely valid and consistent.

Our market assessment of 28 powertrain components reveals seven different powertrain systems (three in the “old world” and four in the “new world”) with different levels of market attractiveness and differentiation potential.

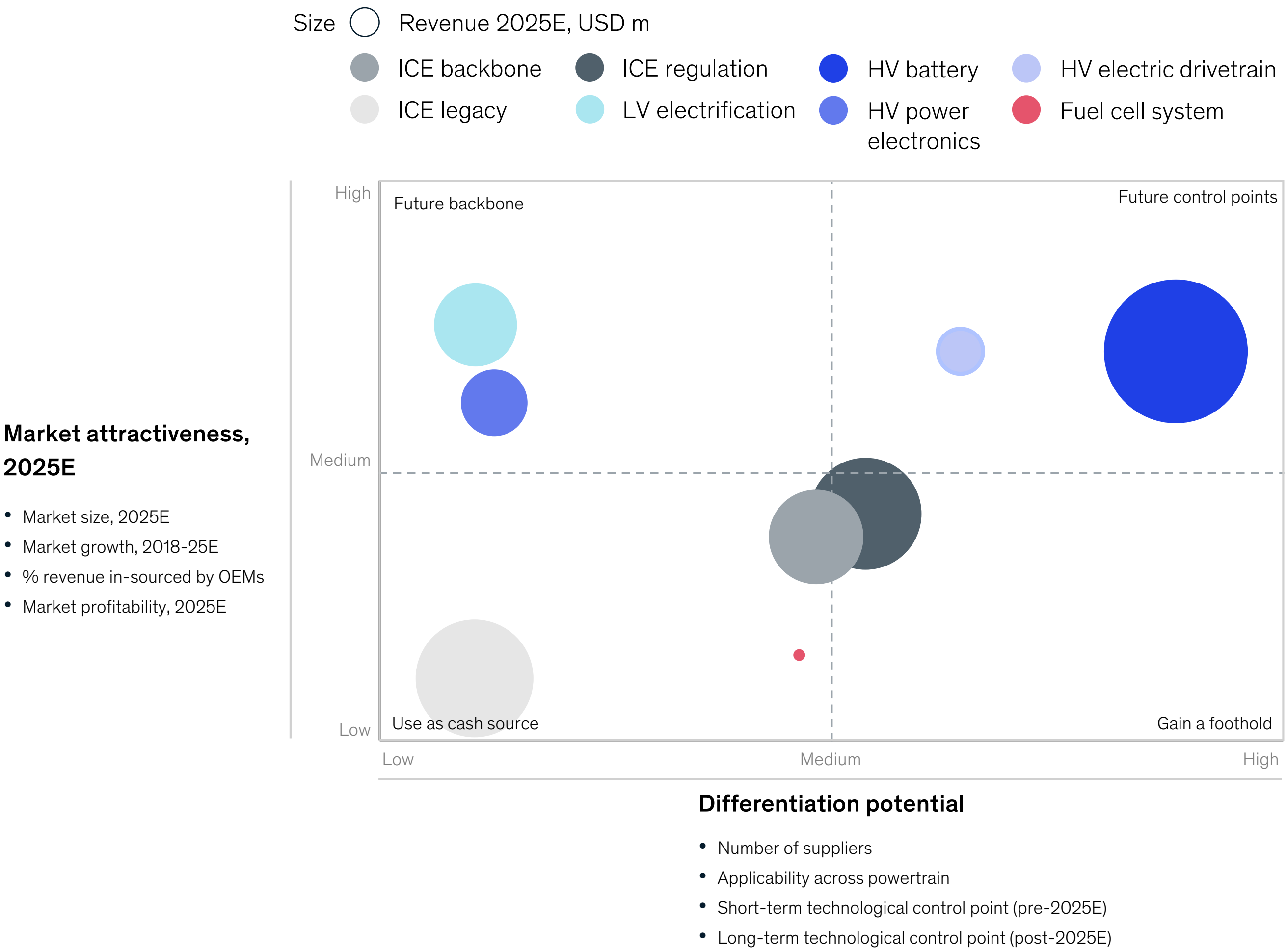
There is a high likelihood for the ICE legacy component market (including the base engine, port fuel injection, and ICE fuel system) to become a commodity business with lower margins and increased consolidation. The resulting overcapacities will impose further price pressure. A winning strategy in these markets will likely be to drive the industry consolidation process, gain scale, and further improve the cost base.

We consider the markets for ICE backbone components (including the transmission, direct injection, thermal management, TCU, and ECU) as attractive for the next five to ten years for several reasons. Optimized ICE and hybrid vehicles will be equipped with innovative direct injection systems and transmissions to further improve the combustion process and vehicle efficiency. ICE backbone components offer CPV and market growth opportunities for suppliers, since OEMs will continue using these components at a higher take rate for their ICE and hybrid vehicles, e.g., for mild and full hybrid vehicles, take rates for direct injection are close to 100 percent.[12] To a certain degree, ICE backbone components are trend resilient, since these components are used in ICEs, MHEVs, HEVs, and PHEVs.

[12] IHS Markit, Alternative Propulsion Forecast, August 31, 2019, https://ihsmarkit.com/products/automotive-light-vehicle-alternative-fuel-propulsion-forecasts.html.

Exhibit 17

Powertrain portfolio analysis – differentiation potential and market attractiveness from a supplier point of view



Source: McKinsey Center for Future Mobility

This broad application provides a natural hedge against the uncertainties of hybrid market uptake. Furthermore, competencies that position suppliers successfully in these markets are equally important for BEVs. Relevant capabilities include a system understanding, software competence, and thermal management. Suppliers that have excelled in these areas in the ICE world are well positioned to grow with their customer base into the new world of (H)EVs.

ICE regulation components (including the aftertreatment system and turbocharger) are likely to constitute an attractive supplier market for the next five to seven years as stricter CO_2, NOx, and particulate emission targets force OEMs to further reduce their vehicles' real-world driving emissions. The result will likely be a CAGR of 3.2 percent through 2025, even though the underlying powertrain market is expected to grow at only 1.3 percent. For gasoline vehicles, the trend towards downsizing goes hand in hand with increased turbocharging. Tighter emission standards require more complex, higher-value (combustion and) aftertreatment systems with, e.g., three-way catalysts, gasoline particulate filters, and lean-burn gasoline NOx control. On the diesel side, we expect the market for vehicles with equal and less than four cylinders to decline most rapidly (-3.5 percent p.a.[13]), driving overall diesel vehicle development.

[13] IHS Markit, Alternative Propulsion Forecast, August 31, 2019, https://ihsmarkit.com/products/automotive-light-vehicle-alternative-fuel-propulsion-forecasts.html.

However, we expect the significant market for large diesel engines to decrease less rapidly (-2 percent p.a. through 2025[14]). Here in particular, CPV in the aftertreatment system will likely increase. Suppliers should carefully analyze their exposure to the diesel market (passenger versus commercial vehicles, large versus small engines) to determine whether it will offer them attractive prospects in the short to medium term. Scale will be relevant for competitiveness, especially in areas that are on the decline. As outlined in Chapter 2, an understanding of combustion and aftertreatment systems is a key success factor for suppliers in these markets.

The e-motor/e-drive market is highly attractive and fast-growing, yet only offers moderate differentiation potential. While e-motors overall represent a commodity market with an established supply base outside the automotive industry, the market for traction e-motors continues to offer several differentiation opportunities (Chapter 2.2b). With today's battery prices in the order of USD 160 to 200/kWh, increasing the efficiency of electric engines can help OEMs reduce costs on the battery side, as less kWh capacity is needed for the same range. With time, the e-motor/e-drive market will become more commoditized. Suppliers will primarily be able to differentiate themselves on the system level through optimal and efficient design (DtV, DtM) and the effective interplay, including thermal management, of all e-drive components.

Power electronics (including inverters, DC/DC converters, and onboard chargers) constitute a fast-growing market, and differentiation will become more difficult as the market grows and matures. While the software and electronics competencies for inverters are key to designing a well-functioning and cost-effective electric powertrain, the market for post these power electronics will remain very competitive, with significant cost pressure for suppliers. A strong focus on rightsizing, R&D cost minimization through modular and scalable platforms, materials cost excellence, and production process/yield optimization will help distinguish high-performing suppliers in this market from their low-performing counterparts.

Today's HV battery cell market is dominated by Asian players. From an individual supplier or OEM point of view, this business is not attractive: it demands high investment and new competencies, and Asian suppliers have a know-how advantage of five to ten years. However, using new forms of industry partnerships to gain a foothold in battery cell production could be essential for certain players to avoid strong dependence on specific suppliers and to get a foot in the door of next-generation battery technology.

Fuel cell commercialization will likely start broadly, with a lag of about one vehicle cycle behind EVs. Suppliers could think about gaining a foothold and managing investment risks through consortia or partnerships. Eventually, R&D amortization will be key and can be achieved through scale and patent protection.

All in all, attractive submarkets will persist over the coming years in both the old and new powertrain worlds. Some crucial competencies – e.g., system engineering, software, and mechatronics – are common to both worlds and will be key to suppliers' successful transition management. If pre a supplier decides to play in the electronics and electrochemistry markets, it will need to gain competence in those areas as well. At the same time, thermodynamics and mechanical competencies will still be fundamental to powertrain engineering, but to a lesser extent.

[14] IHS Markit, Alternative Propulsion Forecast, August 31, 2019, https://ihsmarkit.com/products/automotive-light-vehicle-alternative-fuel-propulsion-forecasts.html.

3.3 How to start navigating the changing powertrain landscape

Today, many suppliers are refining their powertrain portfolio strategies. The optimal portfolio strategy and choice of value pools will vary based on the supplier's existing competencies, the markets where the supplier is active, any long-standing customer relationships, and its target/ambition. A four-step approach can guide suppliers successfully through the powertrain transition regardless of their starting point or aspirations.

The four elements of successful transition management

1 Tangible vision and clear strategy

2 Detailed assessment and global steering of performance focus areas

3 Resource and capability allocation old vs. new world

4 Performance culture and accountability

1. Develop a tangible vision and clear strategy. A clear, communicated strategy is the key to managing the powertrain transition – it is essential for the supplier's success and for buy-in among employees and investors. To manage the uncertainty inherent in this transition, it is important to develop the strategy within a scenario framework. A robust portfolio that will perform well under different scenarios (for regional regulation and electrification momentum, for example) is a cornerstone of success. In this context, clearly defined trigger points (e.g., changes in regulations, incentives, or customer preferences) should be tracked and made available for annual strategic reviews. At the same time, the guiding vision must be broken down into specific, tangible strategic guidelines for the whole organization to follow.

2. Assess performance focus areas granularly, but steer them globally. A successful transformation also depends on rigid performance assessments in order to identify not only focus areas of growth, but also of high performance for the individual supplier. A unified company-wide approach to steering performance cells along clearly defined KPIs is a prerequisite. This allows each supplier to determine promising markets based on the combination of market attractiveness and the company's performance on a product, market, or customer level.

3. Allocate resources through an "old- versus new-world" lens. Resources should be strategically allocated to trend-triggered product development within a defined budget. R&D efforts should focus on future markets, while backbone and legacy markets should follow a low-invest and cash-out logic. Here, suppliers, OEMs, and public sector players need to cooperate in order to bundle research efforts and ensure competitive, viable, and promising solutions for the future of powertrain technology.

4. Prioritize a culture of performance and accountability. Top management should identify the organization's major transition-related strengths and weaknesses. Knowing the specific cultural prerequisites will lay the foundation for the successful transition into the new powertrain world. This transition should be led from the top, with a strong and empowered performance office that steers overall performance and manages compliance with the clearly defined strategy.

The road ahead is obviously challenging: new technological possibilities and tightening environmental requirements are upending many long-standing principles of the powertrain industry. By transferring their existing strengths into the new industry context, joining forces with partners (other suppliers, OEMs, and/or new mobility players), and working proactively, suppliers can manage their transitions successfully and shape portfolios that secure their profit pools in the automotive future.

Appendix

A.1 Regional and component-wise pockets of growth

The market driver categories introduced on a global level in Exhibits 5 and 6 can be further broken down into regional levels. Overall, powertrain supplier revenue is weakest in North America and South Korea/Japan, whereas the strongest growth is in Greater China (Exhibit 19).

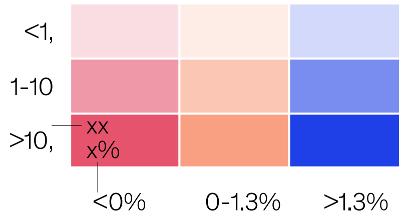
On a component level, different pockets of growth can be identified, e.g., strongest growth is expected for components in LV powertrain and smallest growth for components in diesel vehicles (Exhibit 20).

A.2 Revenue forecasts per component, region, and powertrain

In the following, we show the regional clusters of revenue growth per component as introduced in Exhibit 5.

Forecast to 2025 – regional pockets of growth

Market size, USD billions



Market driver categories

2018-25E	Legacy	Backbone	Regulation	LV electrification	HV power-electronics	HV electric drivetrain	HV battery	H2 electrification	Total
Europe	18.4 -2.5%	38.1 0.9%	14.9 -0.9%	0.2 65.1%	0.8 26.9%	0.6 30.2%	2.2 38.9%	0.0 89.0%	75.3 5.2%
Greater China	20.7 -0.5%	45.8 2.5%	8.8 6.6%	0.0 108.5%	1.7 22.4%	1.2 25.7%	7.3 26.6%	0.0 85.8%	85.6 8.0%
North America	16.9 -2.2%	42.7 -0.8%	5.5 2.9%	0.1 52.7%	0.9 13.3%	0.9 14.1%	4.3 13.6%	- N/A	71.2 1.2%
South Korea/ Japan	10.5 -2.1%	23.9 -1.3%	4.4 1.7%	0.3 24.9%	1.5 7.5%	1.4 7.8%	2.2 18.4%	0.0 16.2%	44.1 1.5%
South Asia	7.3 2.4%	13.2 3.6%	4.0 6.8%	0.1 35.0%	0.0 44.3%	0.0 48.2%	0.0 64.2%	- N/A	24.7 5.0%
RoW	4.7 1.4%	8.6 4.3%	1.7 9.6%	0.0 52.6%	0.0 45.5%	0.0 59.2%	0.0 53.8%	- N/A	15.0 4.7%
Global	78.6 -1.1%	172.2 1.1%	39.3 3.2%	0.6 59.4%	4.9 18.8%	4.1 20.3%	16.1 25.7%	0.04 32.3%	315.9 4.7%

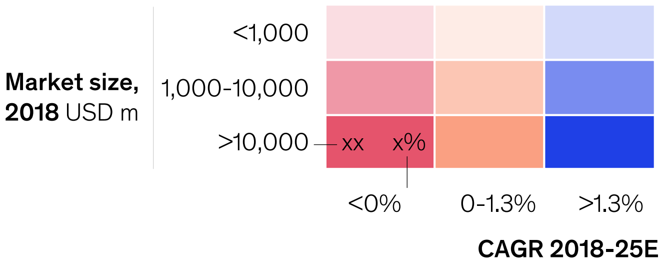
Traditional technologies
6% of total growth 2018-25E

Regulation-driven and innovative technologies
94% of total growth 2018-25E

Components	Legacy	Backbone	Regulation	LV electrification	HV power-electronics	HV electric drivetrain	HV battery	H2 electrification
	Base engine ICE fuel system Air intake Port fuel injection	Direct injection ECU TCU and sensors Manual, automated, and dedicated hybrid transmission Thermal management	Aftertreatment system Turbocharger	LV inverter LV DC/DC LV e-motor LV battery pack	HV inverter HV DC/DC On-board charger	HV e-motor Reducer	Battery cell Power distribution module (PDM), battery management system (BMS), cell management controller (CMC)	Fuel cells Tank

Source: McKinsey Center for Future Mobility

Overview – revenue forecast by component and powertrain



	Combustion system components for ICE and hybrid				Electrification system components					
	Diesel		Gasoline		Low voltage (<=48V)		High voltage (>48V)		Total	
Legacy										
Port fuel injection[1]	6	-7%	1,141	-10%					1,147	-10%
Base engine	10,724	-4%	38,767	-1%					49,491	-2%
ICE fuel system	2,477	-4%	11,013	1%					13,490	0%
Air intake	3,234	-3%	11,286	2%					14,520	1%
Backbone										
Direct injection	6,056	-2%	4,717	8%					10,773	3%
Engine control unit[2]	1,546	-2%	5,644	4%			86[6]	26%[6]	7,276	3%
Man. & autom. transmission[3]	19,941	-2%	104,274	0%					124,215	0%
TCU and sensors	871	0%	5,747	3%			10	29%	6,629	2%
DHT[3]							650	23%	650	23%
Thermal management[4]	3,773	-5%	16,988	-1%	26	93%	1,874	27%	22,661	5%
Regulation										
Turbocharger	3,837	-3%	5,761	8%					9,598	4%
SCR	2,971	13%							2,971	13%
EGR	1,793	-3%	181	40%					1,974	8%
Particulate filter	4,696	-5%	4,324	6%					9,020	1%
Catalytic converter	3,927	-3%	9,043	2%					12,970	1%
LNT	2,753	-2%							2,753	-2%
Electrification										
DC/DC-converter					32	79%	679	22%	711	31%
On-board charger							897	26%	897	26%
Inverter					114	61%	3,302	15%	3,416	20%
E-motor					49	69%	2,955	20%	3,004	23%
Reducer[3]							1,152	21%	1,152	21%
Battery cell					188	50%	13,673	26%	13,861	26%
BMS, CMC, and PDM[5]					260	59%	2,430	25%	2,689	31%
Fuel cells							43	32%	43	32%
Total	68,605	-2%	218,885	1%	669	62%	27,708	24%	315,867	4.7%
Sensors and actuators	8,630	0%	33,307	1%	22	87%	1,083	26%	43,042	3%

Included in all market sizes of other components

1 Incl. indirect injection for diesel engines 2 Incl. all engine control units: aftertreatment, injection, fuel system, PDCU, EHC 3 Excl. TCU and sensors
4 Thermal management is assigned assuming ICE combustion thermal management for comparable ICE motor and determining additional cost for remaining thermal management 5 Power distribution module 6 Only BEV and FCEV revenues

Source: McKinsey Center for Future Mobility

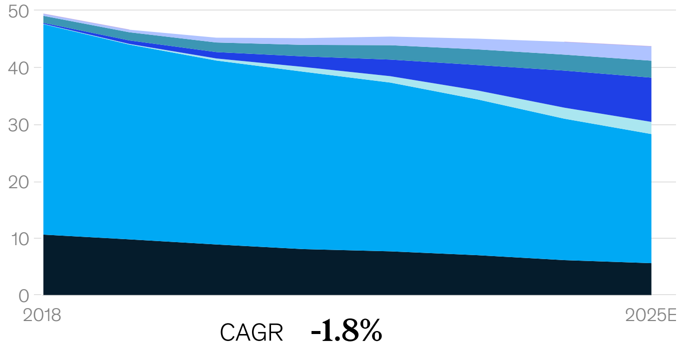
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Global view

USD billions, CAGR 2018-25E in percent

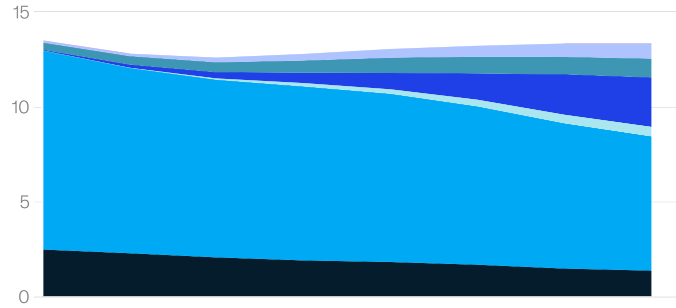
Engine system

Base engine



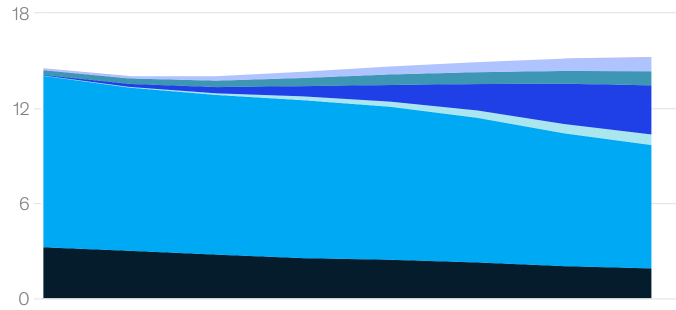
CAGR **-1.8%**

ICE fuel system



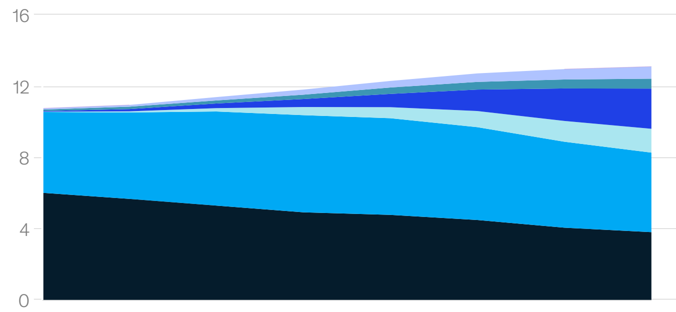
-0.2%

Air intake



0.7%

Direct injection

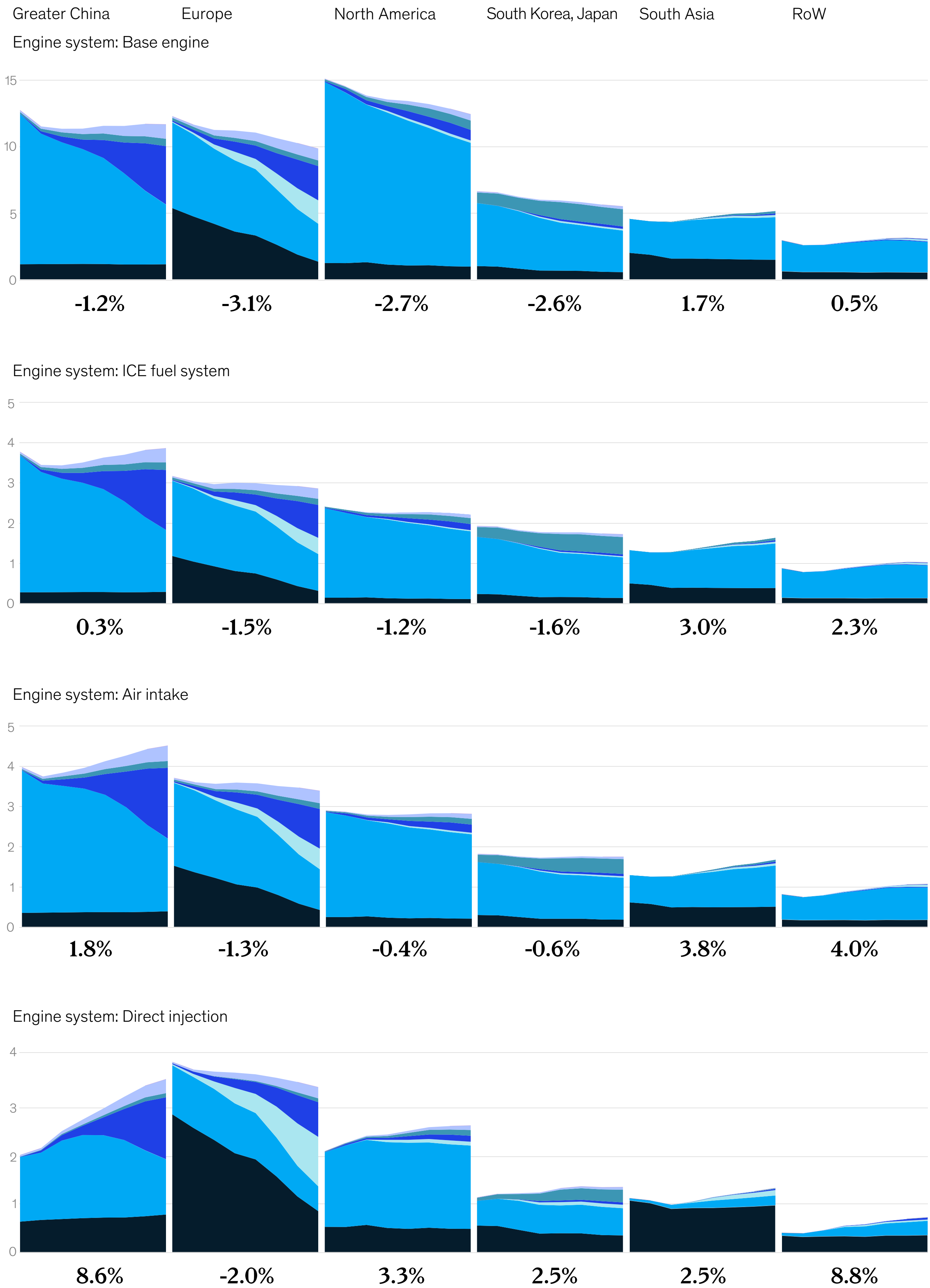


2.9%

FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Regional split

USD billions, CAGR 2018-25E in percent



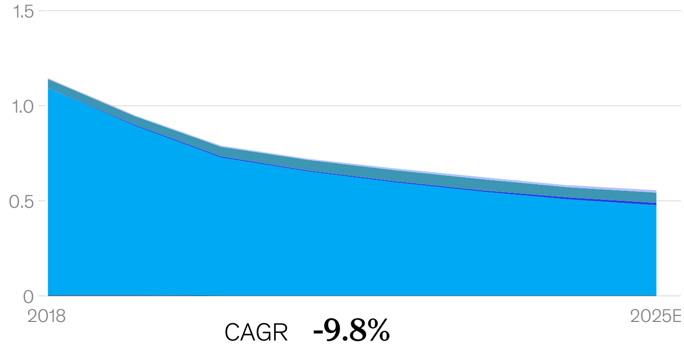
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Global view

USD billions, CAGR 2018-25E in percent

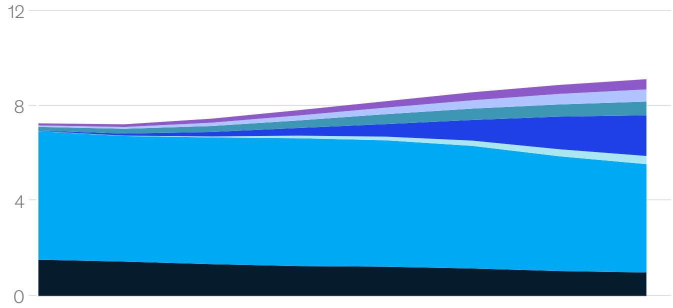
Engine system

Port fuel injection



CAGR **-9.8%**

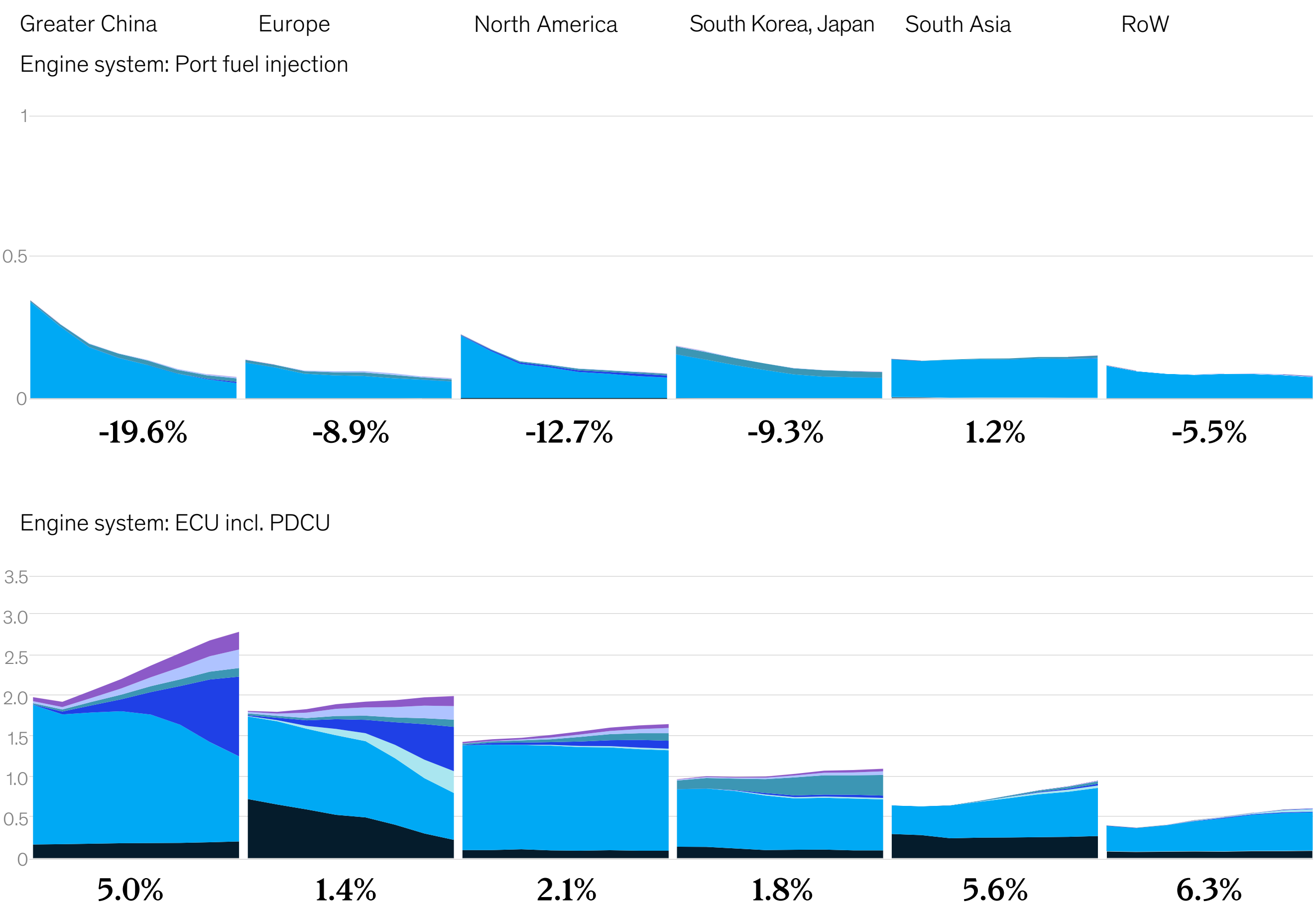
ECU incl. PDCU



3.3%

Regional split

USD billions, CAGR 2018-25E in percent



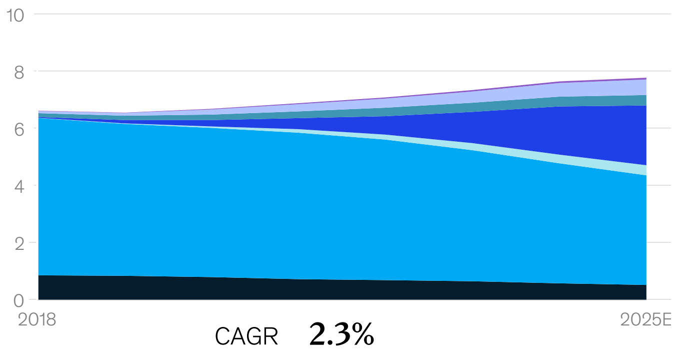
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Global view

USD billions, CAGR 2018-25E in percent

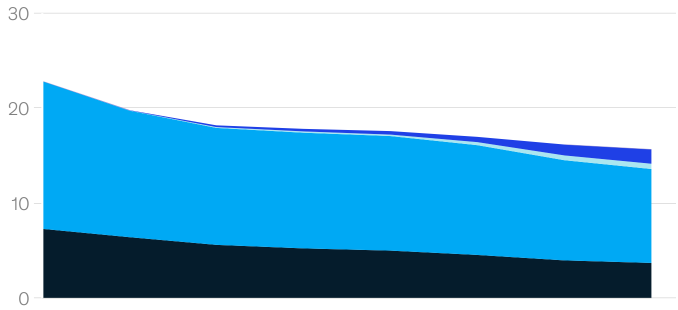
Transmission

TCU and sensors



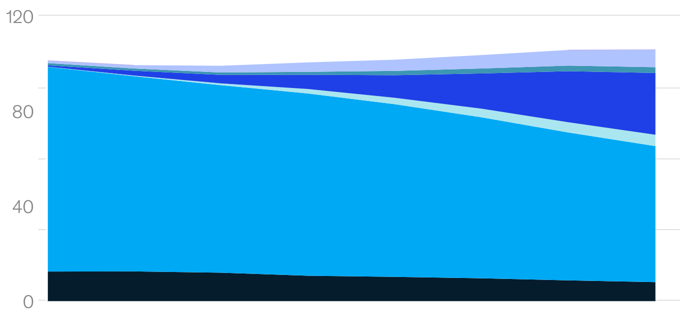
CAGR **2.3%**

Manual transmission (excl. TCU, sensors)



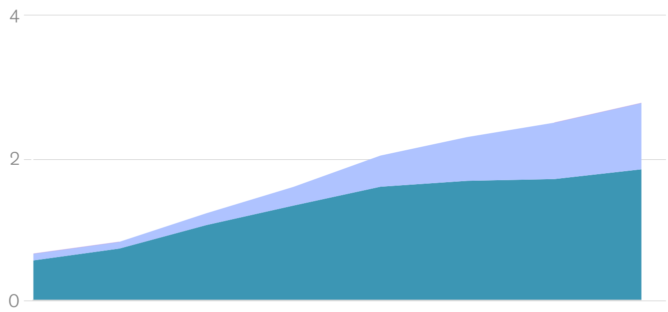
-5.2%

Automated transmissions (excl. TCU, sensors)



0.6%

DHT (excl. TCU, sensors)

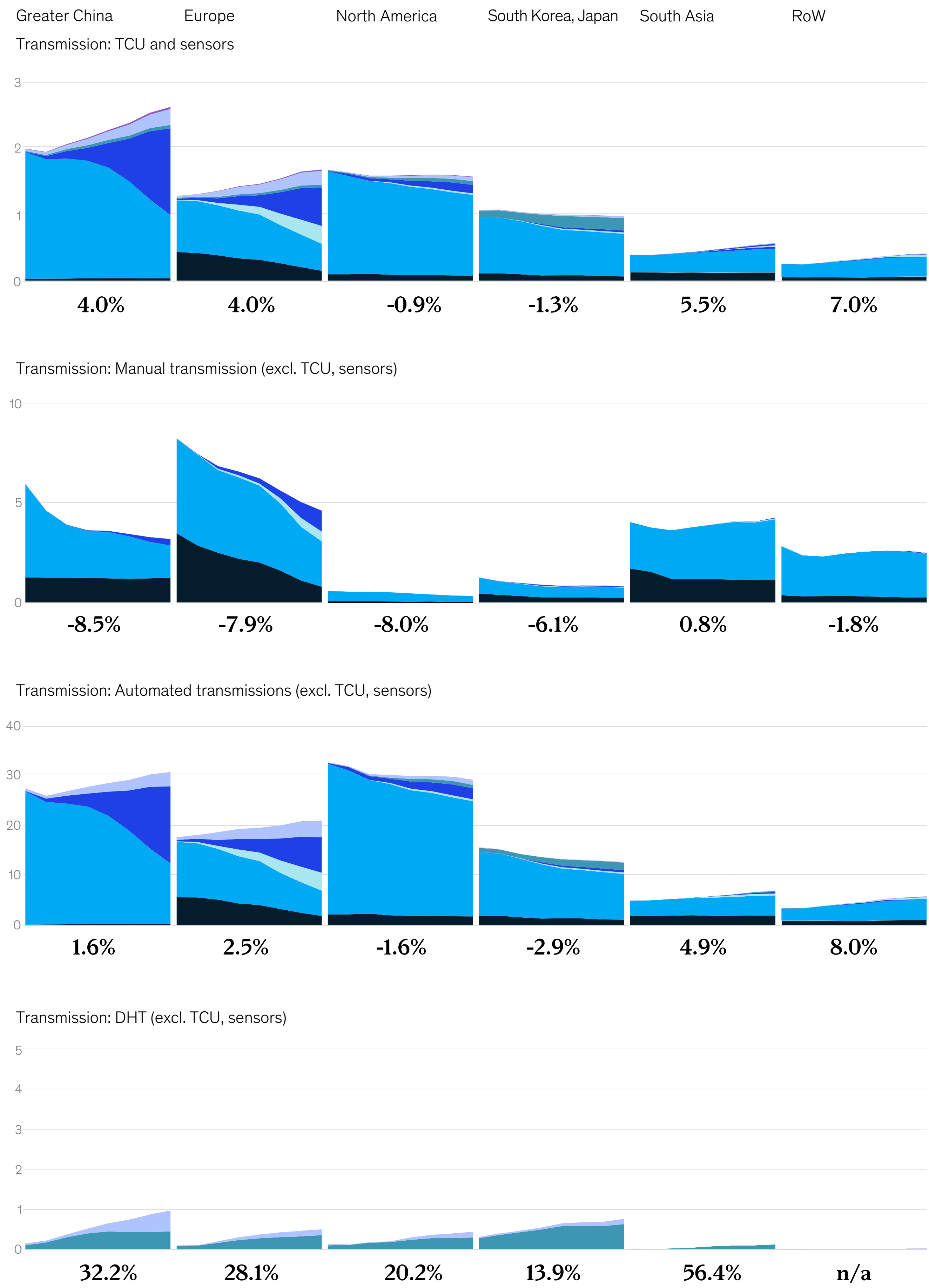


23.0%

FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Regional split

USD billions, CAGR 2018-25E in percent



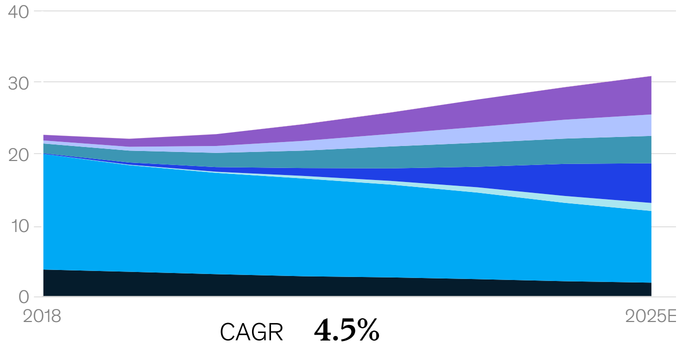
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Global view

USD billions, CAGR 2018-25E in percent

Thermal management

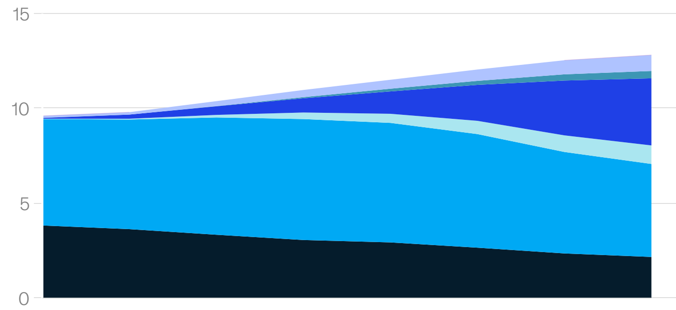
Thermal management



CAGR **4.5%**

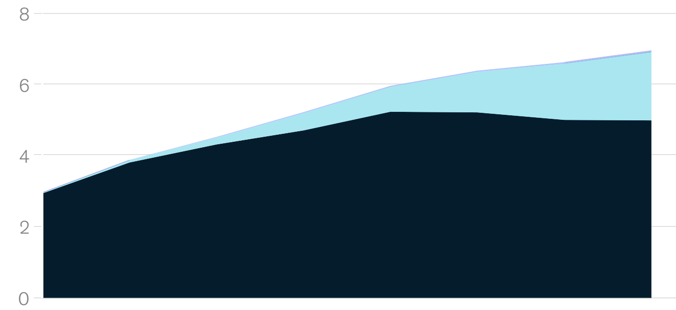
Regulation components

Turbocharger



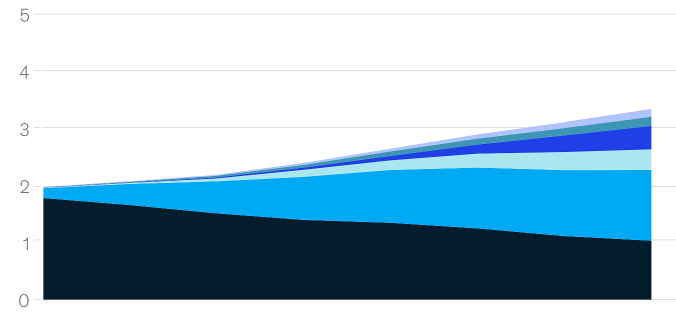
4.2%

Selective catalytic reduction



12.9%

Exhaust gas recirculation



7.8%

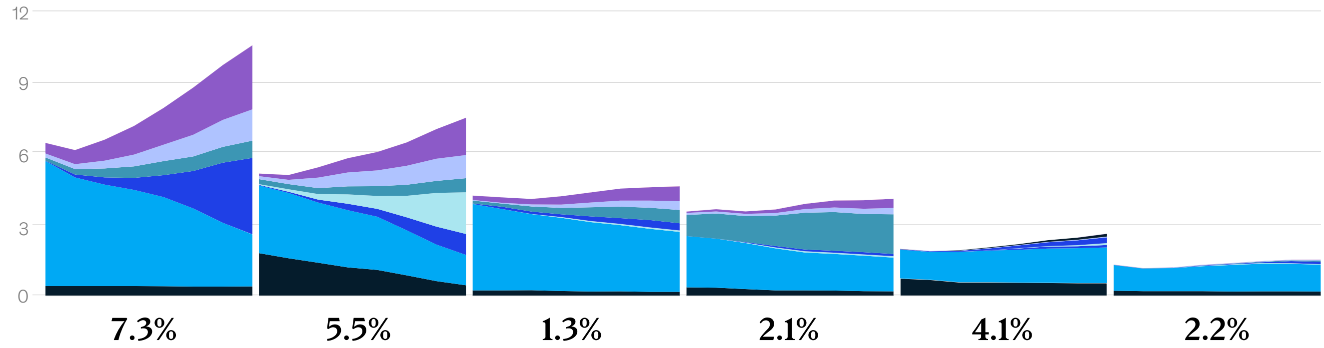
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Regional split

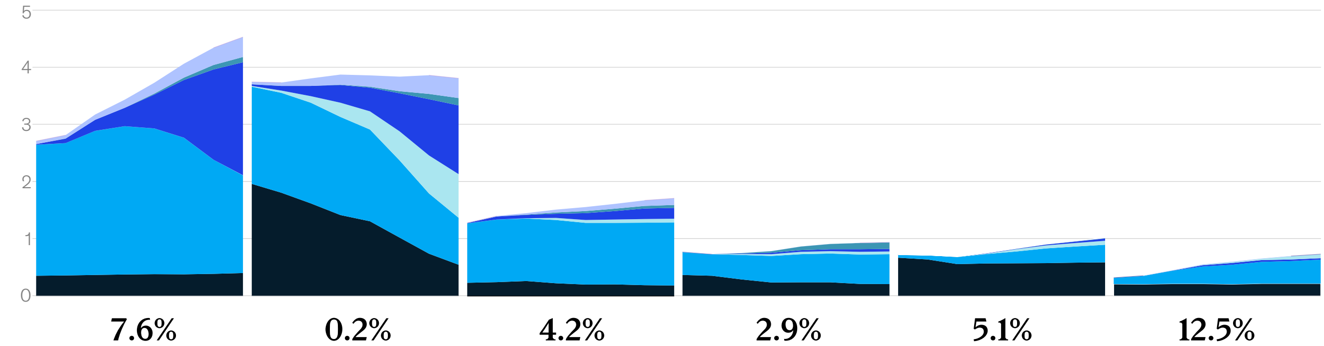
USD billions, CAGR 2018-25E in percent

Greater China | Europe | North America | South Korea, Japan | South Asia | RoW

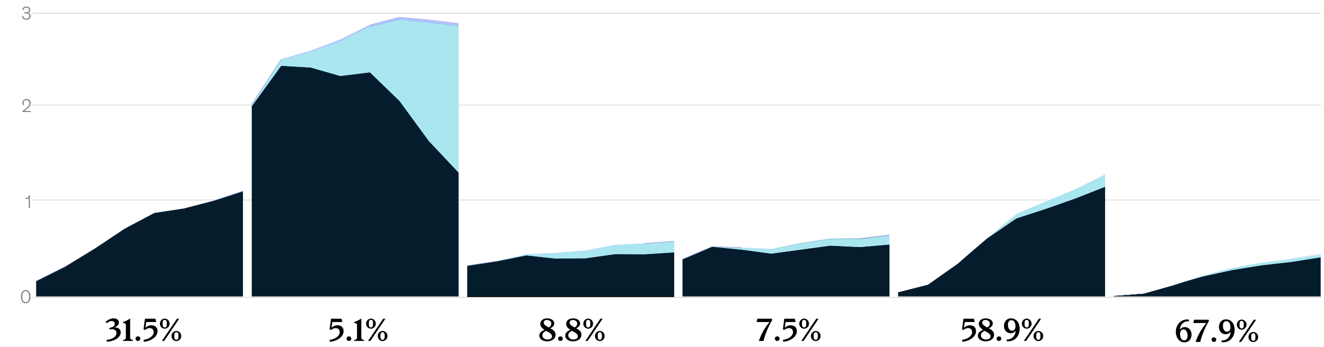
Thermal management



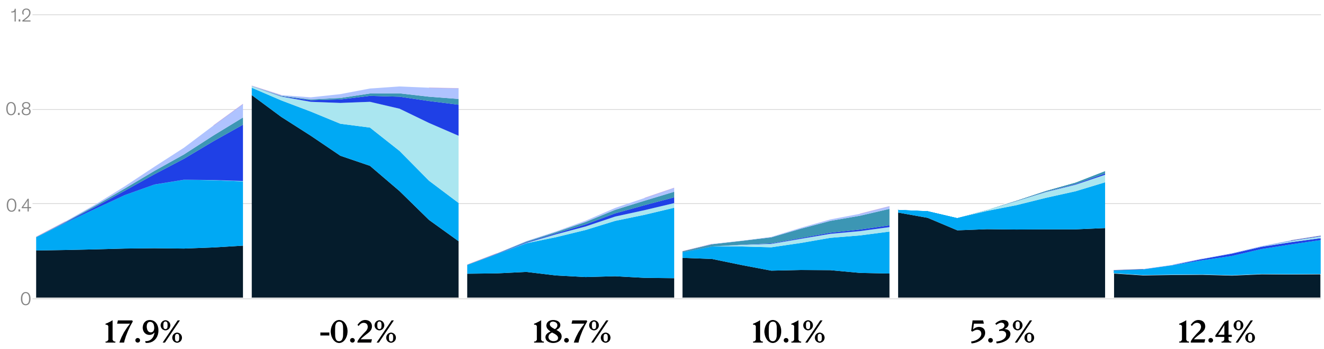
Regulation components: Turbocharger



Regulation components: Selective catalytic reduction



Regulation components: Exhaust gas recirculation



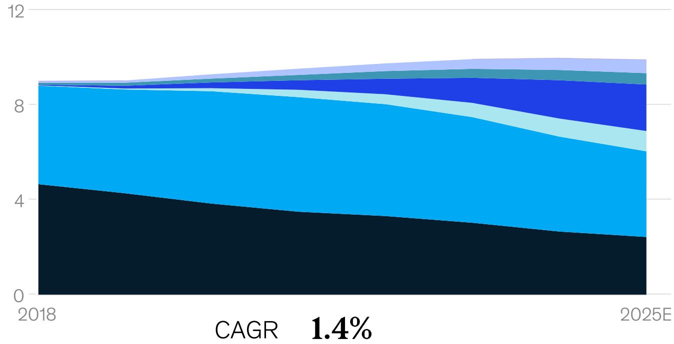
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Global view

USD billions, CAGR 2018-25E in percent

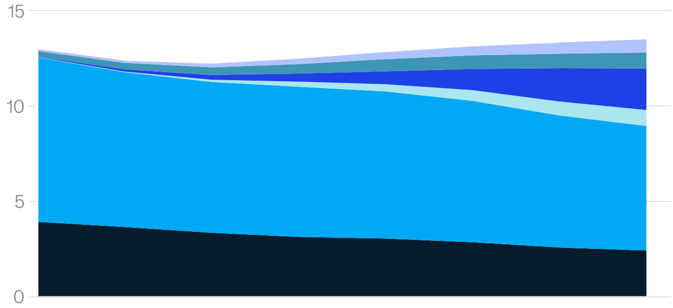
Regulation components

Particulate filter

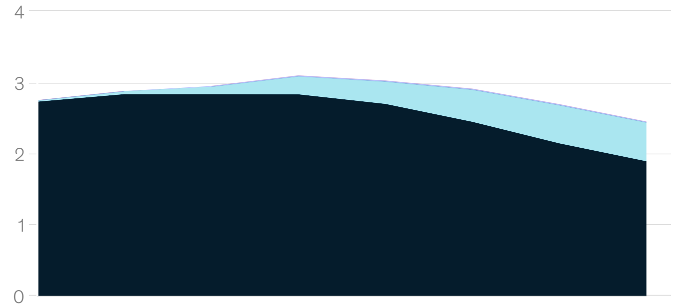


CAGR **1.4%**

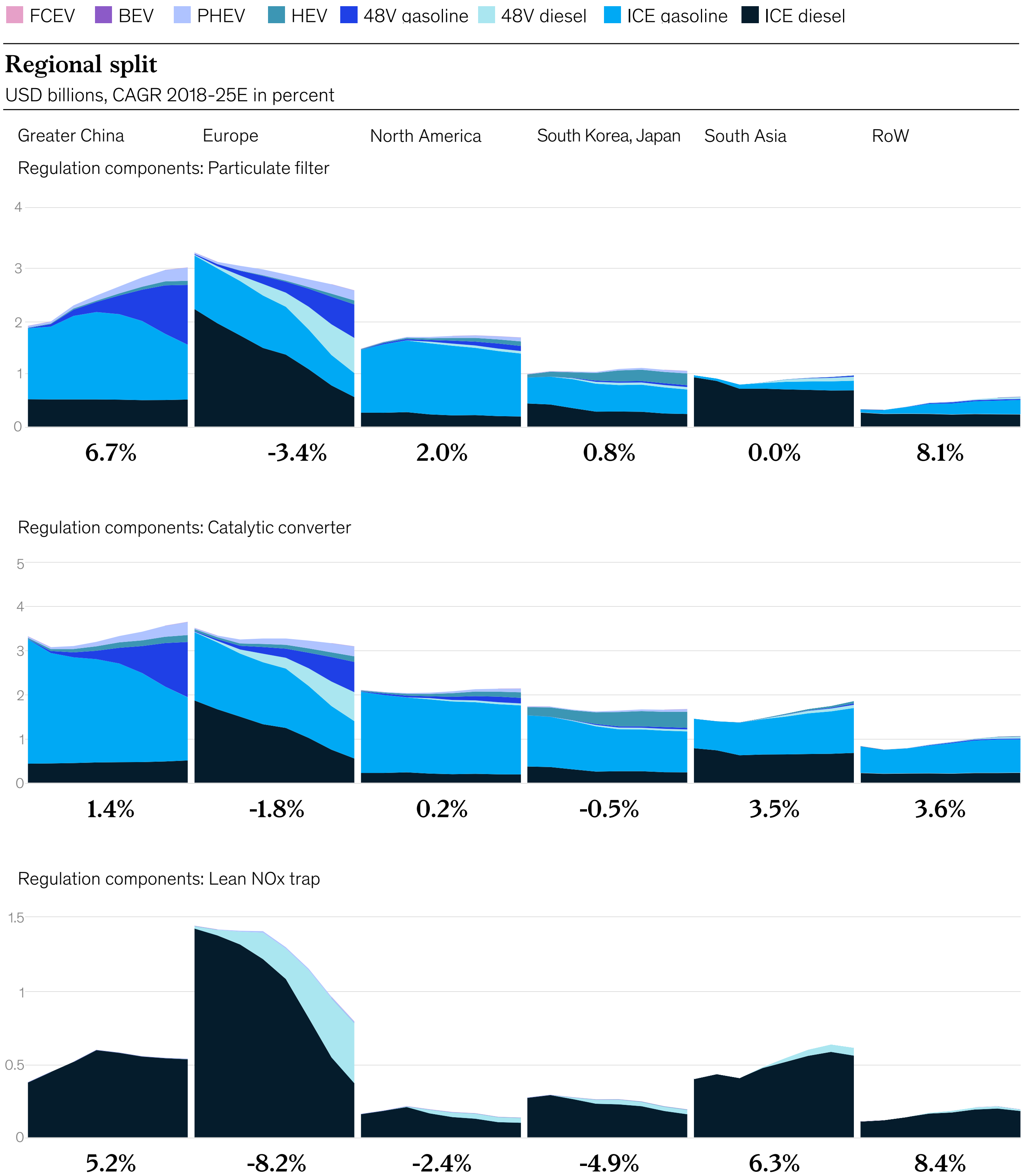
Catalytic converter



Lean NOx trap



-1.6%

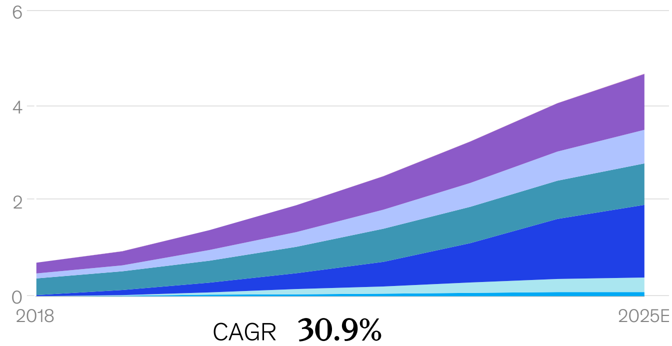

FCEV
BEV
PHEV
HEV
48V gasoline
48V diesel
ICE gasoline
ICE diesel
Regional split
USD billions, CAGR 2018-25E in percent
Greater China
Europe
North America
South Korea, Japan
South Asia
RoW
Regulation components: Particulate filter
4
3
2
1
0
6.7%
-3.4%
2.0%
0.8%
0.0%
8.1%
Regulation components: Catalytic converter
5
4
3
2
1
0
1.4%
-1.8%
0.2%
-0.5%
3.5%
3.6%
Regulation components: Lean NOx trap
1.5
1
0.5
0
5.2%
-8.2%
-2.4%
-4.9%
6.3%
8.4%

FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Global view
USD billions, CAGR 2018-25E in percent

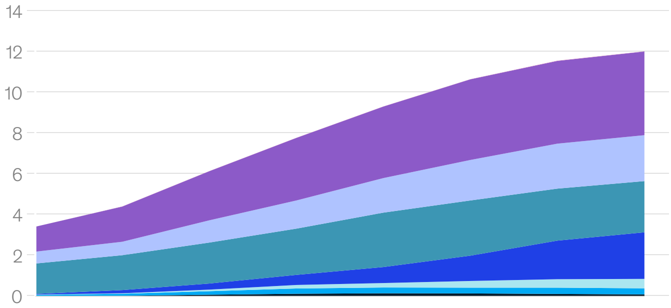
Electrical powertrain

DC/DC converter



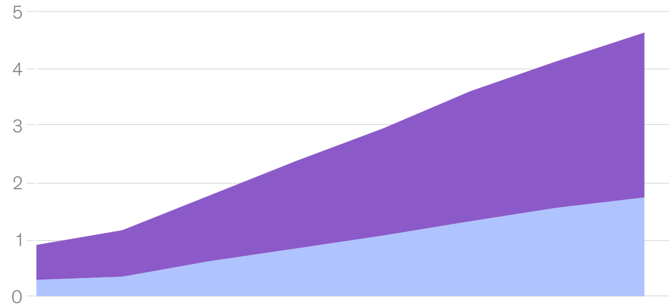
CAGR **30.9%**

Inverter

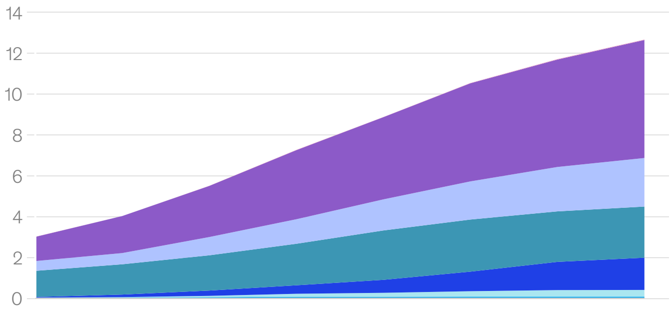


19.7%

On board charger



E-motor



22.8%

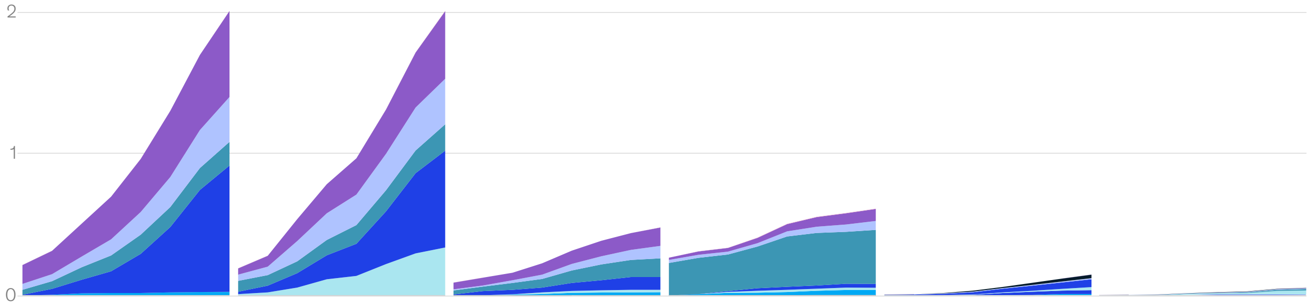
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Regional split

USD billions, CAGR 2018-25E in percent

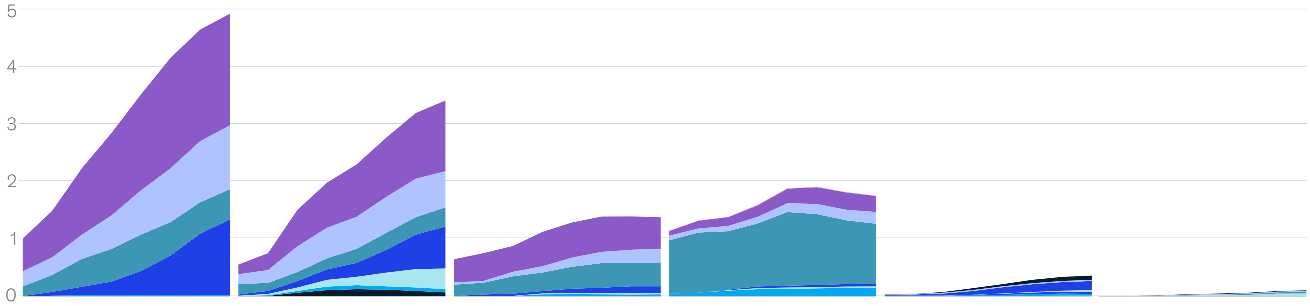
Greater China | Europe | North America | South Korea, Japan | South Asia | RoW

Electrical powertrain: DC/DC converter



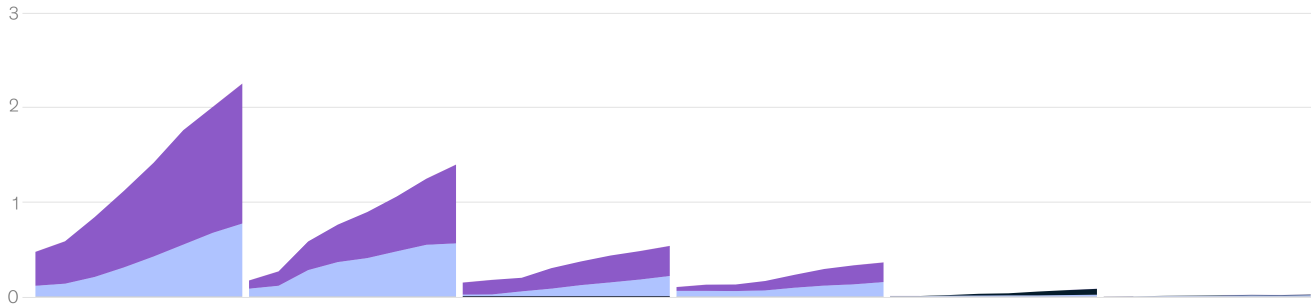
37.6% 39.9% 27.0% 12.6% 57.7% 55.4%

Electrical powertrain: Inverter



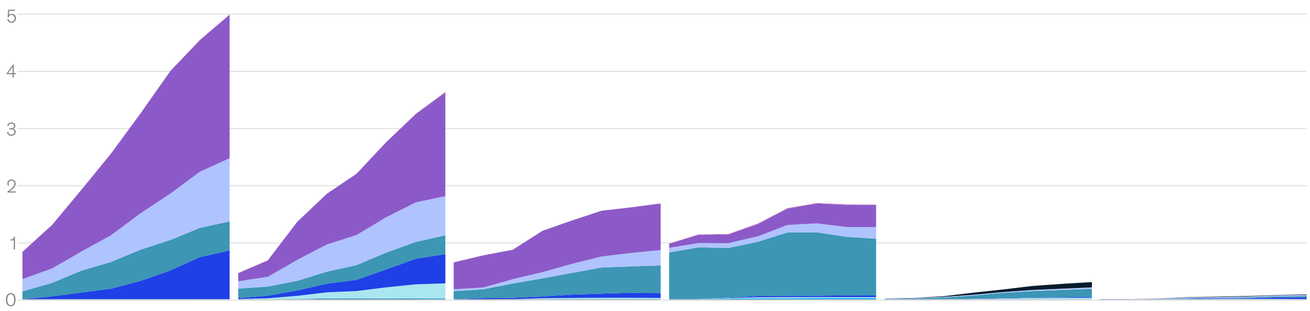
25.5% 29.7% 11.5% 6.3% 39.7% 48.9%

Electrical powertrain: On board charger



25.0% 35.1% 20.1% 20.1% 46.7% 40.1%

Electrical powertrain: E-motor



29.1% 34.2% 14.6% 7.9% 47.7% 50.9%

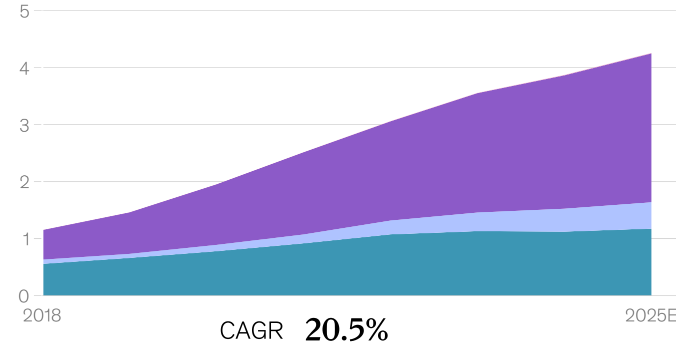
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Global view

USD billions, CAGR 2018-25E in percent

Electrical powertrain

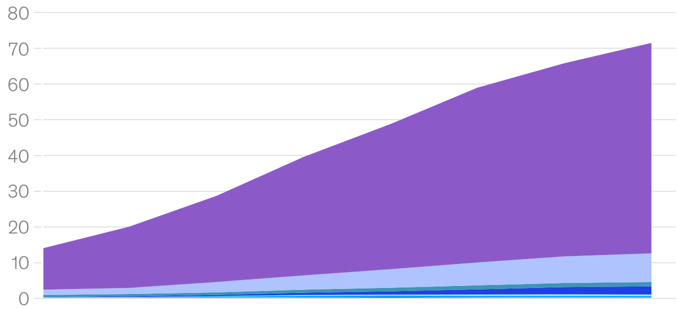
Reducer



CAGR **20.5%**

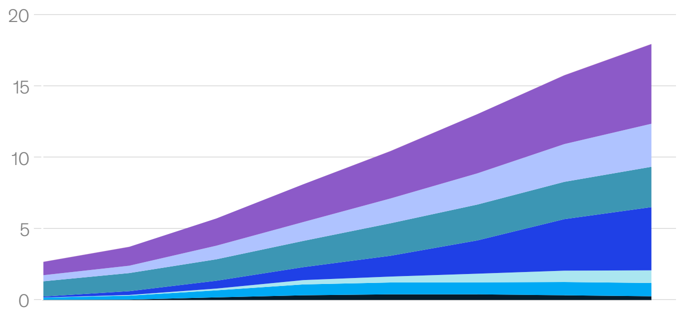
Battery pack

Battery pack (cells and housing)



26.4%

Battery management: CMC, BMS, BJB



31.2%

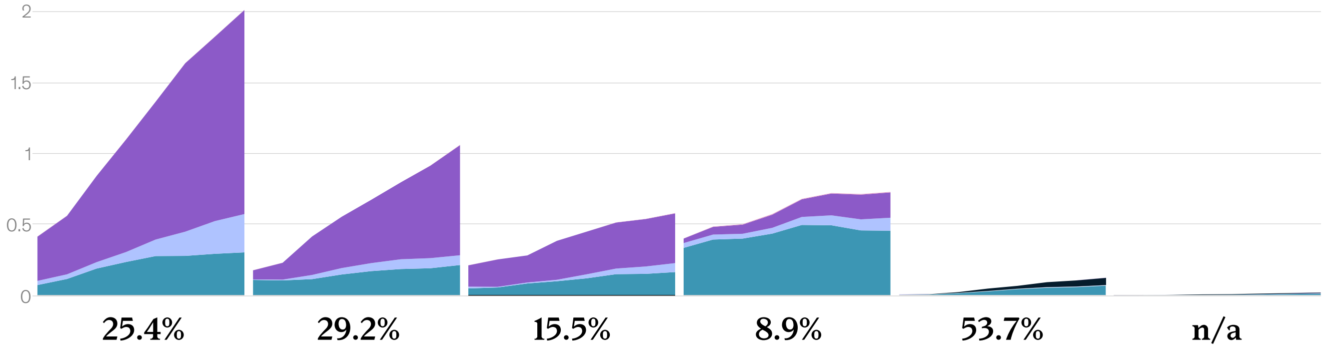
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Regional split

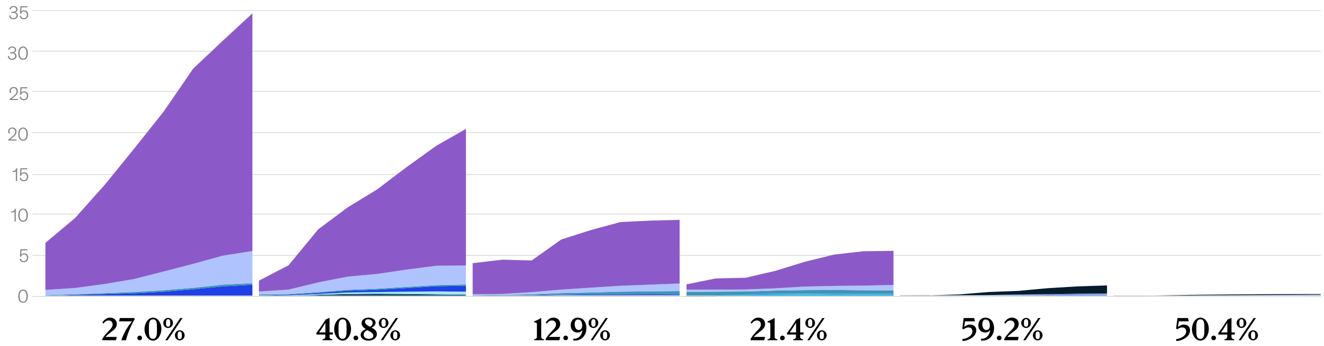
USD billions, CAGR 2018-25E in percent

Greater China | Europe | North America | South Korea, Japan | South Asia | RoW

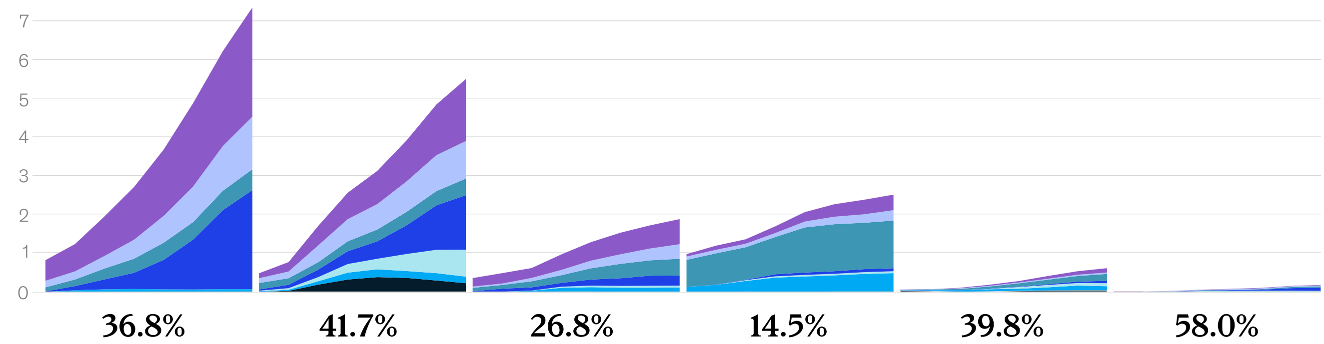
Electrical powertrain: Reducer



Battery pack: Battery pack (cells and housing)



Battery pack: Battery management: CMC, BMS, JB



FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

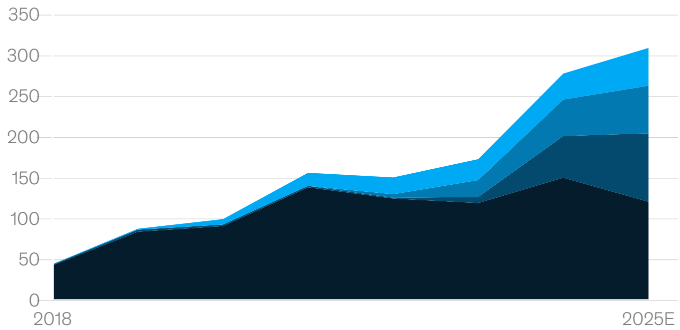
Global view

USD billions, CAGR 2018-25E in percent

Hydrogen fuel cell system

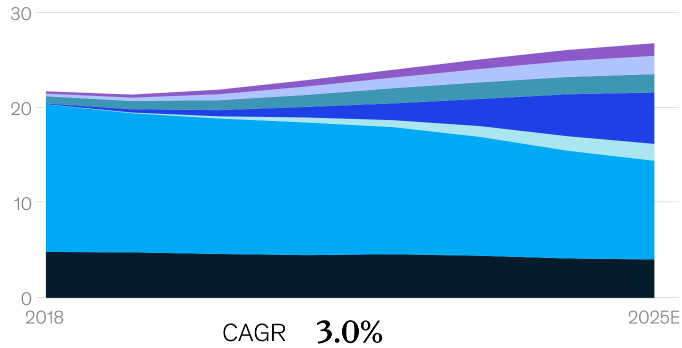
Fuel cells

	CAGR 2018-25
Greater China	85.8
North America	N/A
Europe	89.0
Japan/South Korea	16.2
Global	32.3



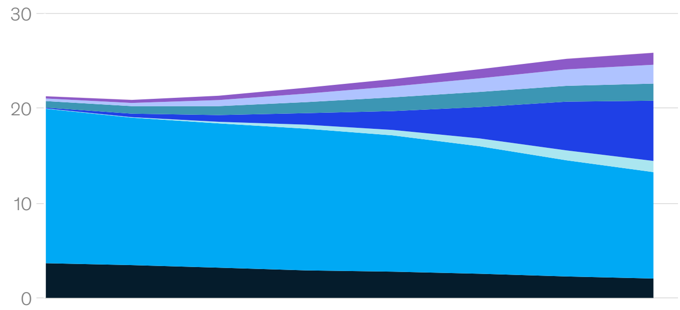
Sensors and actuators

Sensors[1]



CAGR 3.0%

Actuators[2]



2.8%

1 Sensors of the powertrain system, also contained within all market forecasts for the other components
2 Actuators of the powertrain system, also contained within all market forecasts for the other components

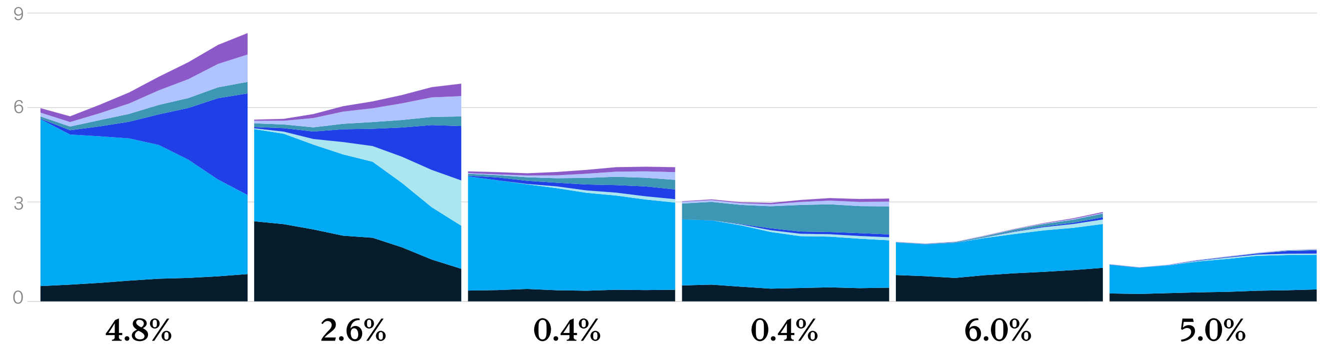
FCEV BEV PHEV HEV 48V gasoline 48V diesel ICE gasoline ICE diesel

Regional split

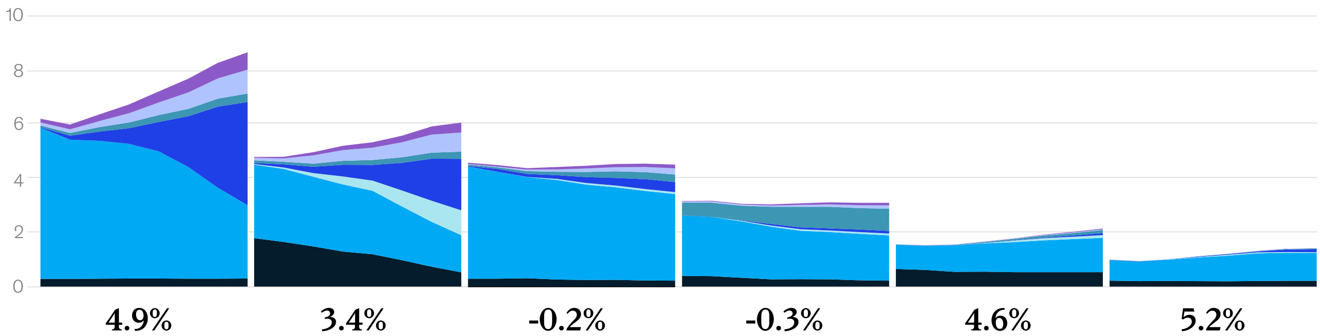
USD billions, CAGR 2018-25E in percent

Greater China | Europe | North America | South Korea, Japan | South Asia | RoW

Sensors and actuators: Sensors[1]



Sensors and actuators: Actuators[2]



1 Sensors of the powertrain system, also contained within all market forecasts for the other components
2 Actuators of the powertrain system, also contained within all market forecasts for the other components

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