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From CO_2 neutral fuels to emission-free driving

Alternative Fuels and Powertrains and their impact on the automotive transformation.

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Preface

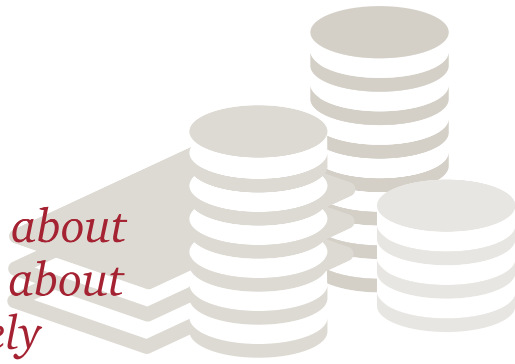
We are at the advent of a series of massive changes to the automotive landscape. Cars are becoming ever-more connected, the sharing economy is starting to make visible inroads into ownership patterns, and autonomous driving looks closer than ever to becoming technically viable. Just as importantly, the mix of fuels that power vehicles, and the powertrains that drive them, will be radically different in 15 years. That poses a series of challenges for automakers and suppliers, who need to juggle their investments in several competing technologies and anticipate future client demands and regulatory requirements around the world.

There is near-consensus that national governments need to regulate CO_2 emissions to help slow climate change, which includes introducing ever-stricter rules for the automotive sector. As a consequence of the Paris COP21 Agreement, targeting zero net CO_2 emissions by 2050 is needed. Even if the US government, the only major hold-out, does not enact national regulation, state- and city-level regulations are likely to have a big impact. And climate change is not the only driver for the regulation of fuels and powertrain technology. Air quality is a major issue, and local authorities are starting to get tougher, both to combat local pollution and in addressing current noncompliance with air quality regulations. Ultimately, buyers and users of cars and trucks are increasingly weary of the negative effects on health and quality-of-living of current vehicles.

Albeit the actual vehicle fleets are transforming gradually, we investigated theoretical scenarios for Germany, in which we hypothesized a full transformation of the light vehicle fleet to either battery-powered electric vehicles (BEVs) running on regenerative electricity, fuel-cell powered electric vehicles (FCEVs) running on hydrogen, or internal combustion engine vehicles (ICEs) running on CO_2 neutral “synfuel”. For each of these scenarios we calculated infrastructure investments and resulting fuel prices when allocating these investments on to the sold fuel.

For vehicle technology, we compared the different powertrain options and plug-in hybrid electric vehicles (PHEVs) in terms of a total-cost-of-ownership (TCO) calculation for today (2017) and the mid-term future (2030). The latter takes into account technological developments, stricter regulation for ICEs and economies of scale.

In addition to our own analysis, we also asked industry insiders for their views at our AutomotiveINNOVATIONS Conference in May 2017 in Frankfurt, Germany. Their responses to our poll make the industry’s uncertainty dramatically clear – for many questions, “no answer” scored higher than any of the given options. And they’re concerned about costs – in fact, the only statement that a majority of respondents agreed with was “Uncertainty about future value of all technologies leads to increasing costs for all powertrain types in the future”.



Automotive executives are uncertain about the future of powertrains and worry about increasing costs. Hence, it is extremely challenging to sharpen the R&D focus and allocate investments for new powertrain technologies appropriately. Readiness in technology and organization are key to be successful in the future.

That is exactly why we undertook this analysis: to help automakers and suppliers understand how different powertrains stack up and what it may mean for their future. We found that the respondents had different understandings of how the different options perform in terms of efficiency. As there is a risk that many industry players may fail to make the right investments to compete in the future, particularly in parts of the value chain that could be fair game for disruption, we aim to provide transparency with our study.

Our analysis shows that the clear winners in terms of well-to-wheel efficiency are battery-electric-vehicles (BEVs). And while consumer preferences still lean towards internal combustion engines (ICEs) – we predict that ICEs will retain the largest market share through 2030 – running the entire fleet on synfuel-powered ICEs won't be feasible in a future where these fuels have to be produced by electric power generated only by renewable resources. In fact, synfuels require more than six times as much electrical energy as battery-powered options. In order to power the complete fleet of light vehicles in Germany by synfuels, therefore, additional 110 nuclear power plants would be needed.

There is also a dramatic difference in the infrastructure costs in theoretical 100% supply scenarios, which range from €300 billion for the BEV scenario, to €480 billion for the FCEV scenario, to €1,370 billion for the synfuel scenario. Assuming an allocation of the infrastructure costs to the fuel price, BEVs would run at fuel costs of €5–7 per 100km, whereas hydrogen fuel costs for FCEVs would range from €7–11, and synfuels would cost nearly four times as much, at €18–26.

For consumers and fleet operators alike, the total cost of ownership (TCO) is also critical to purchase decisions. The biggest contributor to TCO of an automobile is not actual fuel costs, it's the depreciation. And while ICEs and BEVs currently enjoy similar resale values, this fact could change rapidly – for example if major cities implement access restrictions for ICEs. BEVs come with other drawbacks, though, with their current short range and long recharge times. A majority of the industry executives polled expect these drawbacks to persist in 2025 and to impede the widespread adoption of BEVs. These can be overcome by PHEVs, but they may face similar regulatory hurdles in a zero emissions future. Regulation will therefore be a significant catalyst for transformation. If access restrictions for urban areas come widely into play, BEVs will begin to offer real added-value in the mass segment. ICEs will also become much harder to re-sell, compounding the effect. Until this point is reached at about 2025, OEMs and suppliers will continue to generate significant profits from ICEs.

And what about fuel-cell electric vehicles (FCEVs)? At the moment, they aren't yet in series production. Given current expectations on costs, and their strong performance in terms of range (for many car buyers short range is likely to remain a deal-breaker) we believe that FCEVs have the potential to become successful over the longer term in the long-range premium private car segment.

BEVs are the clear winners when it comes to well-to-wheel efficiency and require the least investment of the zero-carbon fuel supply options we studied.

So what does this all mean for OEMs and suppliers, machinery and plant engineering sector, and governments?

OEMs and suppliers need to invest in the new technologies, both to improve product technology and attractiveness to consumers, and to reduce cost levels to be more competitive. That's particularly important given how value creation shifts in BEVs vs. ICEs. To accomplish this, automotive companies will need to recruit, retain, and develop their employees' skills in key areas like electrical engineering. They will also need to integrate new technologies effectively into their R&D, procurement, production and sales processes.

As the transition to electric and electrified powertrains will happen in the next decade, new production equipment will be needed to manufacture the components of alternative powertrains. Production equipment makers are ready to support this transition looking forward to a future with high turnovers.

Governments may set the pace of the transition, well balancing the speed in order to keep the risk of decreasing employment rates in the production of traditional powertrain components low and to build a positive environment for the upcoming employment in future powertrains production. In this way it will be essential for governments to find a way to support competitiveness and stable employment and still foster the transition of automotive powertrains.

On a global level, the strategy towards higher CO_2 efficiency in transportation points to an increasing regional diversity: transportation should use whatever primary energy is most abundant in the respective market – which may lead to different pathways. While Germany, Europe and China converge heavily towards regenerative sun and wind-energy-based electricity, Japan moves its primary energy resource towards LNG. The United States still binge on unconventional oil and gas and may continue to rely on fossil energy for a while. Other regions such as Brazil may continue to leverage their abundant bio-mass based fuels. At least for a transitional period, it seems that the automotive industry will face rather more than less fuel and drivetrain diversity – making investment decisions even harder to take.

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How different powertrains stack up …

… and what it means for the future of the automotive industry.

1 *What drives the transformation towards alternative fuels and powertrains?*

S. 10

Current strong momentum in the transformation is mainly due to local clean air policies and national CO_2 emission regulations.

2 *What would it mean if all light vehicles in Germany switched to one alternative CO_2 neutral fuel?*

S. 13

Additional demand for electrical energy:

+34 %

Electric energy / BEV

+66 %

H_2 / FCEV

+206 %

Synfuel / ICE

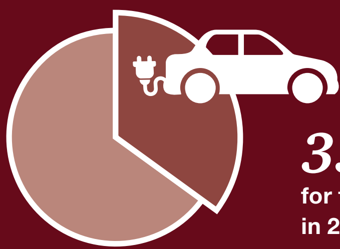
3 *Total cost of ownership and usability are sometimes at odds.*

S. 18

Ability to access zero-emission zones will become a key feature for usability of powertrains.

4 *The total automotive market will grow, electric vehicle market share will expand dynamically.*

S. 21



35 % market share for full electric vehicles in 2030.

5 *Time to act is now.*

S. 24

0 % of industrial leaders we asked think OEMs are well prepared for the upcoming e-technology. Therefore product portfolios and technology roadmaps have to be revised now, and organizational change has to be driven.

Table of figures

A What drives the transformation towards alternative fuels and powertrains?

Current strong momentum in the transformation is mainly due to local clean air policies and national CO_2 emission regulations.

Alternative fuels and powertrains are already a hot topic in all of the big automotive markets. The shift from today's standard fossil fuels, based on refined crude oil, to new sources of energy is receiving intense interest from media, consumers, and governments.

Players all across the industry value chain are taking the developments very seriously, driven by increasing concerns around local pollution and global warming, growing public awareness and calls for action around both issues.

Fig. 1 Drivers for the transformation to alternative fuels and powertrains

1 Local pollution (NO_x, PM, noise)

- **WHO recommendations** for air quality **are hardly met** by any big city throughout the world
- More than **80% of people living in urban areas** are exposed to air quality levels that exceed the WHO limits

2 Global warming (CO_2)

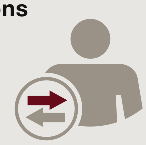
- The **Paris Agreement** entered into force aiming to tackle global warming by
  - Keeping temperature rise **below 2 degrees Celsius**
  - Achieving **zero net greenhouse gas emissions by 2050**

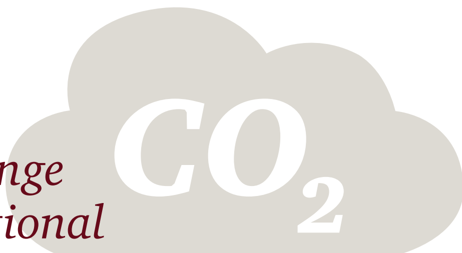
3 Public perception

- Growing number of cities plan to **intensify emission regulations** or even ban combustion engine powered vehicles
- **Real world driving emissions** are becoming more relevant for public perception and legislation

4 Trade policy

- Oil prices have dropped strongly since 2011, reducing the economical importance of reducing net imports
- EU is highly **depending on crude oil imports** (88%) and spent €187bn in 2015; **>70% of imports come from politically unstable regions**





Efforts to slow climate change lead to regulation on a national level and necessitate CO_2 neutral solutions for mobility.

Local Pollution

Big cities and metropolitan areas around the world today face enormous challenges from local pollution. The main air pollutants relevant in this context are nitrogen oxides (NO, NO_2) and particulate matter (PM), both of which have drastic negative effects on human health. According to the WHO, ambient air pollution contributes to 5.4% of all premature deaths worldwide.

Air pollution is mainly an issue for urban areas and in proximity to main traffic routes. Especially in urban areas of low-income countries, the air quality is very weak. Throughout the world, almost no big city can currently meet WHO recommendations for air quality. In fact, more than 80% of urban population around the world is exposed to air quality levels that exceed the WHO limits.

Global Warming

Greenhouse gas emissions are an important driving force of global climate change. CO_2 is the most important greenhouse gas, and road transport contributes approximately 17% to the global emission of CO_2.

In December 2015, during the UNFCC Conference in Paris, the Paris Agreement was adopted; it entered into force in November 2016. As of May 2017, it was ratified by 147 nations. The main goal of the Paris Agreement is “Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change.”

In order to achieve this goal, it is necessary to achieve net-zero emissions of greenhouse gases by the second half of the century.

What is the difference between carbon dioxide (CO_2) and air pollutants?

Conventional fossil fuels such as Diesel and Gasoline belong to the family of hydrocarbons (C_yH_y). In an ideal combustion process, they are oxidized, resulting in H_2O (water vapour) and CO_2 as reaction products. CO_2 is not harmful to the human body, but contributes to the greenhouse effect and drives climate change.

However, in an actual combustion process, unwanted side products arise. Due to their negative effect on human health they are considered as pollutants. Nitrogen oxides (NO_x) and particulate matter (PM) belong to this group.

Public awareness of emissions and pollution issues

Public awareness of air pollution and demand for action has increased strongly within the last years. Within Germany, air quality has improved slightly in the last two decades. However, the air quality goals set by the EU are still often violated, leading to an increased pressure on municipal authorities to take measures in order to improve air quality. Demand for action on climate change continues as well.

Many consumers have had their faith in the automotive industry's progress on both fronts severely shaken by the recent discussions around the manipulation of laboratory tests certifying the emissions of passenger cars. ICEs are in the spotlight. Many consumers now view real world emissions of diesel engines in a very critical light, despite their excellent performance in terms of fuel efficiency and future capability of fulfilling NO_x regulations. Consumers want assurance that the cars they drive are not harming the environment.

Trade policy

Although oil prices have dropped strongly within the last few years, the dependence of most industrialized countries on oil imports still motivates governments to increase their degree of energy independence. The political stability in most of the countries with large proven oil reserves is rather low and trading relations are prone to uncertainty and shocks.

The result: more regulation

Local pollution problems, global warming and increased public awareness are all resulting in a drive to implement regulations to restrict internal combustion engines and stimulate electric vehicle usage.

A growing number of cities plan to intensify emission regulations or even ban combustion engine powered vehicles. In particular, diesel powered engines are in the focus, as their NO_x and PM emissions during real world use are higher than what has been measured in laboratory tests. And while a new generation of diesel engines may be able to cope with the challenge of reducing emissions, it is not guaranteed that the general public will regain their trust in diesel engines. At the same time, many industrialized countries are developing governmental programs to stimulate electric vehicle sales and usage.

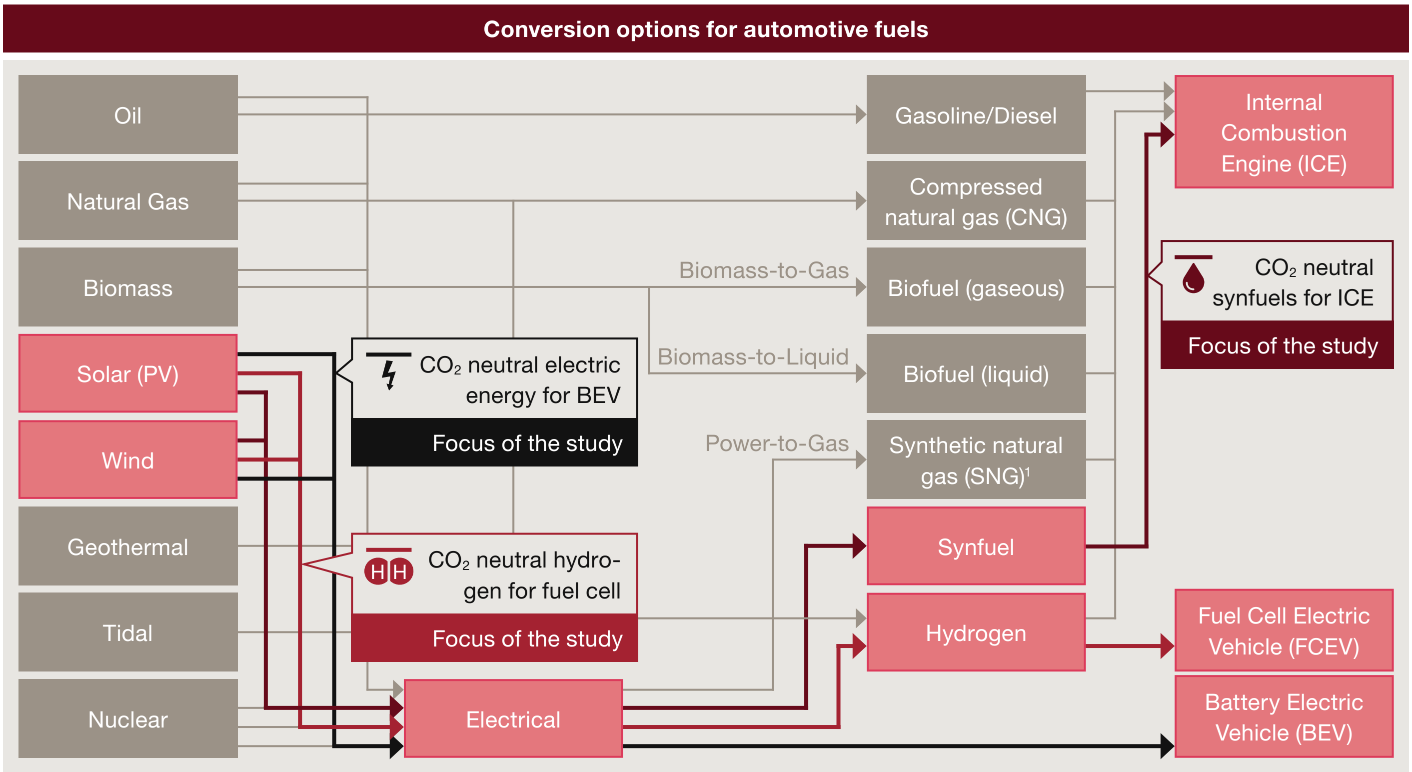
Local pollution and noncompliance with air quality regulations push local authorities to introduce emission-related access restrictions.

B What would it mean if all light vehicles in Germany switched to one alternative CO_2 neutral fuel?

The well-to-wheel efficiency of 70% for BEVs outnumber all other CO_2 neutral options.

To gain greater insights on what the future might look like, we devised several scenarios of what the future might hold for different types of powertrains. We started with the premise that countries will honor their Paris commitments to achieve zero net greenhouse gas emissions over the long-term (by 2050). We then investigated pathways for exclusively CO_2 neutral energy fuels, covering the whole production and usage chain from "well to wheel". We excluded some energy sources that are not currently used in larger scale applications, or where conversion costs are much higher. Figure 2 shows which paths were included and excluded from the scope of the study.

Fig. 2 Focus of the study – selection of conversion paths



Focus of the study

[1] Also referred to as "E-Gas".

Only CO_2 neutral energy sources were selected for the analysis, thus fossil oil and gas were excluded. Biomass, geothermal, and tidal energy do have a limited availability in Germany and are thus not included in the analysis. Although nuclear energy is considered as CO_2 neutral energy source, we don't see a realistic chance for a large-scale renaissance of nuclear power at least in the western world. Thus, only wind and solar photovoltaic power are included as CO_2 neutral energy sources.

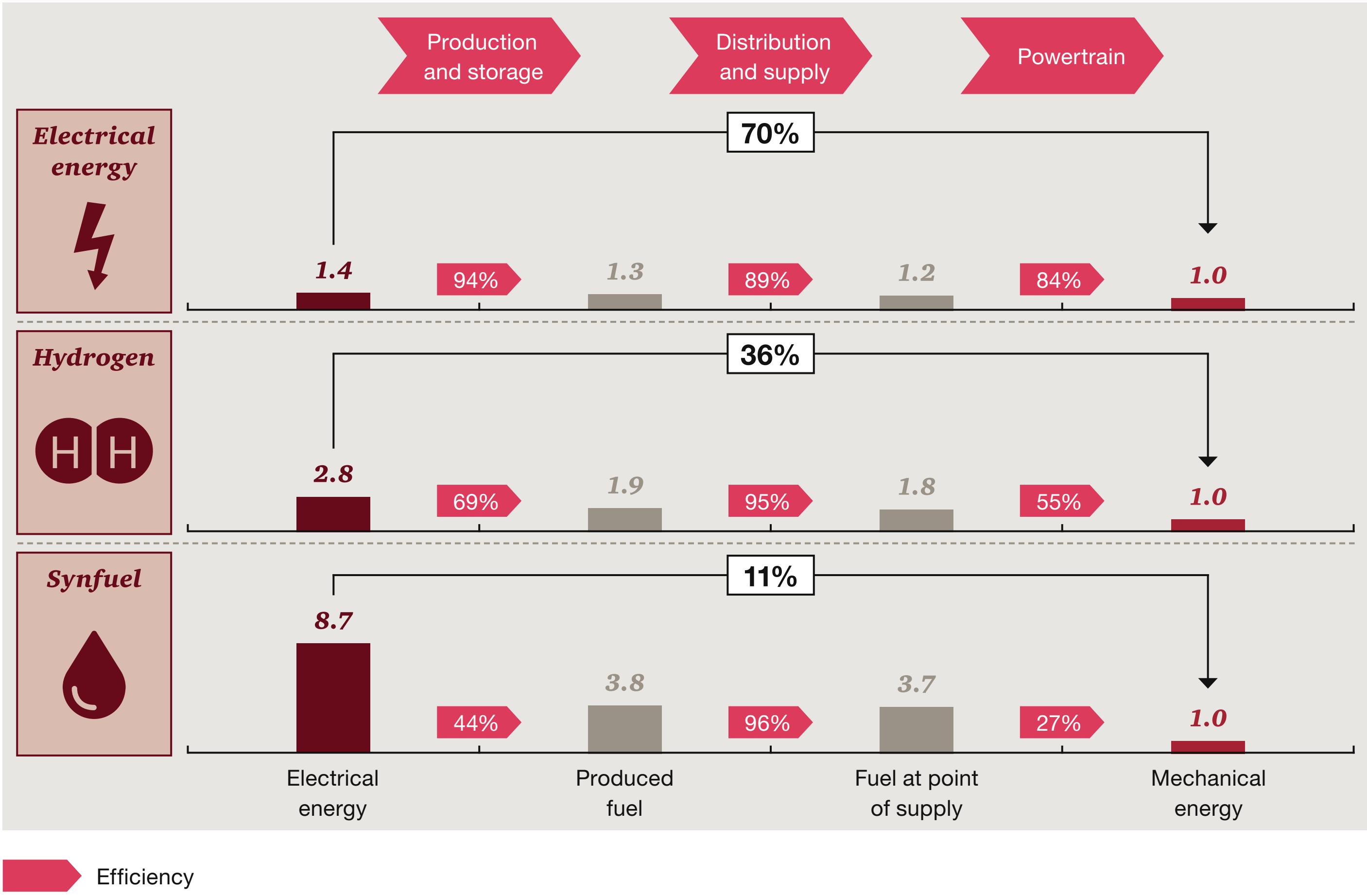
Coming from wind and solar power, our primary focus was on three different ways to power vehicles using carbon neutral energy sources:

- ***Electric power that can directly be used in BEVs***
- ***Conversion of electrical energy to hydrogen and subsequent use in fuel cell electric vehicles (FCEV)***
- ***Liquid synthetic hydro-carbon fuels ("synfuels") produced by a "Power-to-Liquid" method and burned in ICEs***

Our results show that there are dramatic differences in the well-to-wheel efficiency of these paths. Figure 3 shows these sharp contrasts. Although the distribution and supply of electric energy for BEVs is less efficient than for the other paths, the overall well-to-wheel efficiency for BEVs is highest with 70%. For the hydrogen path, it is only at 36%, whereas for the synfuel path it drops as low as 11%. In order to get 1kWh mechanical energy at a car's wheel, one therefore has to produce 1.4kWh electrical energy for a BEV, 2.8kWh for a FCEV, and 8.7kWh for an ICE powered by synfuel.

Many industry players haven't yet recognized the efficiency advantages BEVs can provide – just 32% of the automotive executives we polled agreed with the statement "The most energy efficient pathway is using electric energy for battery electric vehicles".

Fig. 3 Efficiencies (%) and energy demand (in kWh) in the production chain of CO_2 neutral[1] fuels per kWh of mechanical energy



[1] Assuming CO_2 neutral energy is used throughout the whole process chain.

Electricity demand levels and investment needs differ dramatically too

The dramatic differences in production efficiency have significant implications for electricity demand over the mid- and long-term.

In order to compare the different fuels we modeled full supply scenarios for Germany. In each scenario, one of the three fuels (electric, hydrogen, synfuel) is used as the sole energy supply for all of the motorcars licensed in Germany. Based on the efficiencies given in Figure 4, the total annual distance driven by German motorcars in 2015 (619 billion kilometers) and the average energy consumption of a motorcar (20kWh per 100km), the fuel energy and electrical energy needed for all motorcars per year was calculated for each scenario.

Today's annual demand for electric energy in Germany is at about 525 TWh (Source: BDEW for year 2015), including virtually no demand for any of these alternative powertrains.

What are synfuels?

Synfuel is used as a collective term for synthetic hydrocarbons, produced from electrical power. CO_2 is used as a carbon source. We considered use of CO_2 from the ambient atmosphere, as other CO_2 sources such as from steel production or biomass, are limited in their availability. All synfuels (and gaseous synthetic fuels, such as SNG) rely on a first step where hydrogen gas is produced from electric power by electrolysis. The hydrogen and CO_2 are processed to methanol, which is then processed to a synthetic fuel with characteristics similar to diesel or gasoline fuel. The methanol route represents analternative to the Fischer-Tropsch synthesis, but is considered to be more efficient.

Fig. 4 Alternative full supply scenarios for Germany: Total demand of electrical energy and investment needs (in billion €)

	Additional demand for electrical energy[1] (TWh)	Production and storage: Production	Production and storage: Storage	Infrastructure: Distribution	Infrastructure: Point of supply/ filling station	Total
Electrical energy	176 (+34 %)	176 • e.g., ~35.000 wind power plants	18 • **61 GWh storage capacity** (e.g., 200 large scale systems)	58 • **Investments to strengthen electrical grid**	48 • **26m low power,** 300k high power **charging points**	301 • **58% for electrical power plants**
Hydrogen	344 (+66 %)	402 (344) • e.g., ~70,000 wind power pl. • 6,200 electrolysers, 7.5MW each	7 • **Compressed H_2** tanks close to electrolyser (180 kg H_2 each)	44 • **Investments to strengthen electrical grid**	27 • **6,200 filling stations**, each with 10 dispensers	479 • **72% for electrical power plants**
Synfuel	1,079 (+206 %)	1,239 (1,079) • e.g., ~200,000 wind power plants	0 • **Use of existing** fuel bunkers	132 • **Use of existing** transport trucks to distribute liq. fuel • Invest for electrical grid	0 • **Use of existing** facilities	1,371 • **79% for electrical power plants**

525 Total demand[2] (Germany, 2015)

Electrical power plants | Fuel plants

[1] Additional demand for automotive fuels, assuming full supply of all light vehicles in Germany.
[2] Total demand for Germany as of 2015 (Source: BDEW).

Mobility-demand for electricity in the pure electric scenario would be at 176TWh, approximately one-third of today's total annual energy demand. Covering this demand would require a range of investments in additional power plants, grid-level electrical storage, and improvements to the transmission and distribution grid. There will also be a need for demand management around vehicle charging, in order to prevent distribution systems from overloading. And naturally a full network of private and public charging points will need to be built. All told, this adds up to €301 billion in investments.

If all vehicles shifted to hydrogen for FCEVs, the energy demand would be larger than in the pure electric scenario. There would also be a number of additional investments needed, for example, for the transmission grid, as well as for electrolyzers and filling stations. In total, we assumed 6,200 electrolyzers and filling stations. Since each filling station has a compressed H_2 tank, one advantage of the hydrogen scenario is a decoupling of energy supply and demand. We estimate total investment costs in this scenario at €479 billion.

For the synfuel scenario, the mobility-demand for electric energy would necessitate large investments for power plants and an enhanced transmission grid. Even though almost no investments would be needed in the supply infrastructure, the total investment needed would still be a staggering €1,371 billion to power the full supply for the total car park – and that's only in Germany.

Fig. 5 Full supply scenario for Germany: Estimation of variable costs (€/MWh_{fuel})

	Production and storage		Infrastructure		Add. price components		End user price
	Production	Storage	Distribution	Point of supply	Margin	Tax	
Electrical energy	85	7	65	33	19	64	273
	• Estimated average LCOE	• CAPEX for storage	• Grid fee	• CAPEX and OPEX for charging points	• 10% of cost	• Energy tax 20.50€/MWh • 19% VAT • No further fees	• 27.3€-ct/kWh
Hydrogen	170 (146)	3	32	9	21	45	279
	• Electrical power and electrolyzer CAPEX/OPEX	• CAPEX for storage	• Grid fee for electric energy	• CAPEX and OPEX for H_2 filling stations	• 10% of cost	• No energy tax • 19% VAT	• 9.3€/kg
Synfuel	219 (193)	0	50	3	27	57	357
	• Electrical power and synfuel plant CAPEX/OPEX	• OPEX for storage of 0.18€/MWh	• Grid fee for electric energy	• OPEX for filling station	• 10% of cost	• No energy tax • 19% VAT	• 3.3€/L

Electrical energy   Fuel processing

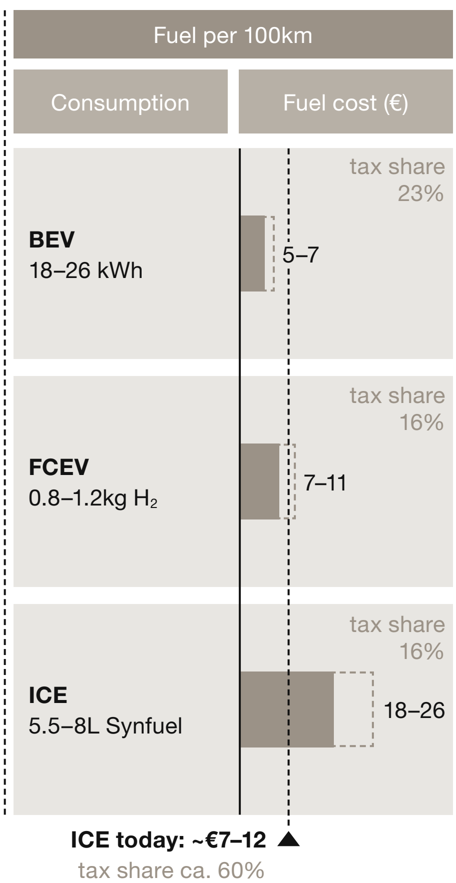
Hydrogen and synfuels are less energy and cost efficient, but are essential for applications with high energy demand.

Fuel costs are much lower for both BEVs and FCEVs

We calculated a fuel price for end users for each scenario, assuming an allocation of the investments to the fuel price, additional operational costs as well as margins and taxes.[1] Compared to today's fossil fuel costs of ~€7–12 per 100km, lower fuel costs in the full electric scenario of €5–7 per 100km are expected. In the hydrogen scenario the same range as today is expected, whereas in the synfuel scenario fuel costs are about twice as high as today's fuel costs.

Having analyzed the zero-CO_2 fuel full supply scenarios for three fuel types, we will shift gears in the next chapter and focus on the total cost of ownership (TCO), thus also covering technological attributes of existing traditional and alternative powertrains.

Large scale supply of light vehicles with CO_2 neutrally produced synfuel seems not feasible.



If all light vehicles in Germany switched to BEVs, demand of electrical energy would grow by 176TWh annually, 34% of today's total demand for electrical energy.

[1] For the electrical energy pathway we included an additional energy tax. Further fees, especially the German renewable energy fee, were not accounted for here, as the cost for electrical energy is already based on an assumed non-subsidized price for renewable energy of 85€/MWh.

C Total cost of ownership and usability are sometimes at odds

Ability to access zero-emission zones will become a key feature for usability of powertrains.

Moving away from the hypothetic full supply scenarios, we now focus on the technology and TCO of vehicles. We defined several reference vehicles employing different powertrains, in order to compare features and costs. Our base car is premium mid-sized, with 200kW peak output rating. Figure 6 shows the vehicles we defined, which include a PHEV option as well.

The ICE vehicle includes a 48V electric machine as integrated-starter generator for boost and recuperation function. Our fuel cell electric vehicle includes a high-voltage battery (25kWh) that is charged directly from the external electrical grid. This realistic "plug-in" configuration lowers the dependence of the FCEV on hydrogen infrastructure and uses the better conversion of electric energy directly from the battery for low distances, while using hydrogen on long distances or low battery charge.

We assume that PHEVs and FCEVs are operated with electrical energy from the grid at 60% of the driven distance (short distance rides) and the rest in "range extension mode" with energy from the combustion engine or the fuel cell.

Fig. 6 Attributes of reference vehicles by powertrain

		ICE	PHEV	BEV	FCEV
Components	Engine	200 kW	160 kW	–	–
	e-Engine	~15–20 kW	~80 kW Peak, ~50 kW Cont.	~200 kW Peak, ~100 kW Cont.	~200 kW Peak, ~100 kW Cont.
	Electric Drive	–	Inverter/DCDC/OBC	Inverter/DCDC/OBC	Inverter/DCDC/OBC
	Tank	~60 l (fuel/synfuel)	~60 l (fuel/synfuel)	–	~5 kg @ 700 bar (hydrogen)
	Battery	<1 kWh (48 V-battery)	~10 kWh (HV-battery)	~60 kWh (HV-battery)	~25 kWh (HV-battery)
Range	Non-Electric	700 km	700 km	–	–
	Electric	–	<50 km	~400 km	~500 km + ~150 km

Due to uncertainty about future value, all powertrains will suffer from high depreciation.

Car buyers focus both on total cost of ownership (TCO), and on more qualitative factors that we term “usability”. While BEVs have a clear lead in TCO, they still fall short in some of the key usability criteria like range and refueling time.

We looked at fuel cost, depreciation (variabilization of vehicle cost), and other factors (tax, maintenance and bonus) in determining the TCO of each reference vehicle. In order to estimate the TCO for 2030, a cost model for each powertrain was developed, including technological progress mainly for batteries and power electronics, as well as more stringent legal requirements for combustion engines. On the other hand, we anticipated that both ICEs and PHEVs will benefit from additional efficiency improvements.

BEVs lead the pack both today and in the anticipated future when it comes to fuel cost. PHEVs benefit from some of the same advantages as BEVs, giving them a lower fuel cost than conventionally powered ICEs. For synfuel powered ICEs, the high cost of producing synfuel leads to very high fuel costs.

We calculated vehicle costs based on a cost model that assumes a lifetime production of 2 million vehicles, in order to allow for a fair comparison of the powertrain types (see Figure 7). Actual vehicle costs could, of course, vary somewhat, however there are some significant trends which are already apparent. Cost of ICE powertrains will increase, due to more restrictive legislative demands regarding efficiency and emissions. The cost of key components of alternative powertrains will decrease due to economies of scale; that’s already being seen in price reductions on battery cells, electric motors, and power electronics. Fuel cell costs are more of a question mark; the extent to which the technology proliferates will have a big impact on whether or not the cost curve comes down dramatically.

Other costs include taxes and one-time purchase bonuses that lead to reduced costs for electrified powertrains in 2017. While maintenance costs are expected to be lower for BEVs and FCEVs, these only played a minor role in our calculation.

Fig. 7 Mobility costs for reference vehicles

		TCO/mobility cost in €/100km		Usability		
		2017	2030	Range (km)	Refuel time (min)	Access to ZEZ[1]
	Content	Fuel cost; Depreciation; Other (tax, maintenance, insurance and bonus)		Assuming full tank	Full reload	Zero local emission and low noise
Diesel/ gasoline	ICE/Mild Hybrid	55.9	54.5	700	1	✗
Electrical energy	PHEV	52.2	54.8	700	1	O
Electrical energy	BEV	49.9	50.7	400	30–360[2]	✓
Hydrogen	FCEV	55.5	56.2	600	3	✓
Synfuel	ICE/Mild Hybrid	69.3	64.4	700	1	O

Good performance   Medium performance   Weak performance

Bonus of €4,000 (BEV/FCEV) and €3,000 (PHEV) included for 2017. Powertrain costs calculated for 2 million vehicles lifetime.

1 ZEZ: zero-emission zone.

2 Largely depending on charging power.

Weak range and infrastructure impede the widespread adoption of BEVs.

Although the total cost of ownership of our reference vehicles is lowest for BEVs today, and will stay lowest in 2030, the difference between the powertrain types is relatively small. Depreciation represents a major portion of total costs. In our model we assumed a constant rate in loss of value for all vehicle types. Depending on factors like the extent of proliferation of zero emission zones, these values could still change significantly.

Figure 7 compares costs for our modeled vehicles, as well as for vehicles powered with conventional ICEs. In terms of day-to-day usability, the conventional ICE offers a bigger range and faster refueling, but won't be able to access zero-emission zones. Whether or not local governments will permit synfueled ICEs to enter emission free zones is still unclear. Plug-in hybrids could be a way to achieve quick refueling and high range, while enabling a zero local emission drive mode when running on electric power in urban areas. Currently it is also not yet clear if PHEVs will be granted access to zero-emission zones, though, and this could vary according to the exact wording of local legislations.

FCEVs and BEVs emit zero local emissions at any time and will have access to zero-emission zones. Pitfall for BEVs are the short range and slow recharge time. FCEVs combine long range, fast refill and accessibility to zero-emission zones. However, for both BEVs and FCEVs limited availability of charging points and refill stations, respectively, is an issue.

Uncertainty about future value will increase

Total cost of ownership of vehicles in this segment is dominated by depreciation. All powertrains suffer from large uncertainty about their future value. For ICEs it is mainly due to the threat of non-accessible zero-emission zones, whereas PHEVs, BEVs and FCEVs might quickly become outdated faster due to the pace of progress in technological development.

FCEVs are expected to become an attractive solution for the long-range premium vehicle segment.

D *The total automotive market will grow, electric vehicle market share will expand dynamically*

In 2030 42 million EVs will be sold globally, representing a market share of 35%.

In order to be able to project future sales on a global level, the development of the drivers has to be investigated globally as well. Besides the already discussed powertrain costs and vehicle TCOs, we see legislation, infrastructure, and public perception as main drivers for the transformation.

Fig. 8 Estimated development of drivers over time (2017–2030)

	2017	2020	2025	2030
Legislation[1]	• **120g CO_2/km (NEDC)** • Introduction of first eco vignettes • Market activation for alternative powertrains (APTs) • Low oil prices reduce the positive perception of alternative powertrains	• **95g CO_2/km (WLTP)** • Market activation in place for APTs (strong legislative push) • Increasing oil prices foster importance of alternative powertrains	• **<75g CO_2 (WLTP)** • **First Prohibition of ICEs in cities with pollution issues** • No further legislative push for alternative APTs • Increasing oil prices foster importance of alternative powertrains	• **<60g CO_2 (WLTP)** • **Widespread prohibition of ICE in inner cities of highly developed countries** • No further legislative push for alternative APTs • Dependency on oil imports have negative impact on ICE
Infra-Structure	• **Weak public charging infrastructure** • H_2: Globally >200 filling stations	• **High speed chargers along main transport routes** • Private inductive charging • H_2: Globally >1,000	• **High speed charging available in most areas** • Public inductive charging • H_2: Globally ~4,000	• Increasing build-up of infrastructure • **H_2: Globally ~11,000**
Powertrain cost	• **Lowest cost for ICEs,** ~50% surcharge for PHEVs, BEV and FCEV cost 2.5–3x higher	• **BEV cost ~2x of ICE,** as ICE cost increase and battery cost decrease	• **BEV cost ~40% higher than ICE**, FCEV ~80% more expensive than ICE	• **BEV and ICE almost at same cost**, FCEV still ~50% above ICE cost
Public Perception	• **ICE with best usability** in focus • Most customers of APTs are companies, innovators	• **Still ICE with best usability in focus** • Most customers of APTs are early adopter (some private customers)	• **Growing focus on BEVs and FCEVs** • Increasing customers of APTs	• **Due to driving prohibitions, ICEs become unattractive** • Wide basis for customers of APTs

Driver is suitable for APT · Driver is moderate for APT · Driver is unsuitable for APT

[1] Based on Local Pollution, Global Warming & trade policy.

APT: Alternative Powertrain

Domestic content of powertrains produced by German OEMs will grow slower.

Most important legislative driver are the CO_2 emission regulations, which are motivated by the effort to limit climate change. The average limit is expected to drop to <60g/km in 2030 and also the test cycle will shift to WLTP from 2018 on. Local pollution in urban areas may urge authorities to introduce stricter regulations regarding access and may lead to prohibition of ICEs first in cities with pollution issues and successively to more and more inner cities, especially in developed countries.

We expect fuel cell technology to become especially applied for long-haul and heavy duty demands. With initial help of governmental subsidies, we expect more than 11,000 filling stations by 2030 globally.

For BEVs, the electric infrastructure for charging will be build up as a high speed charging network earlier. First, by 2020, high speed chargers will be available close to main traffic routes and by 2025 they will be available in most areas.

Outlook on powertrain cost

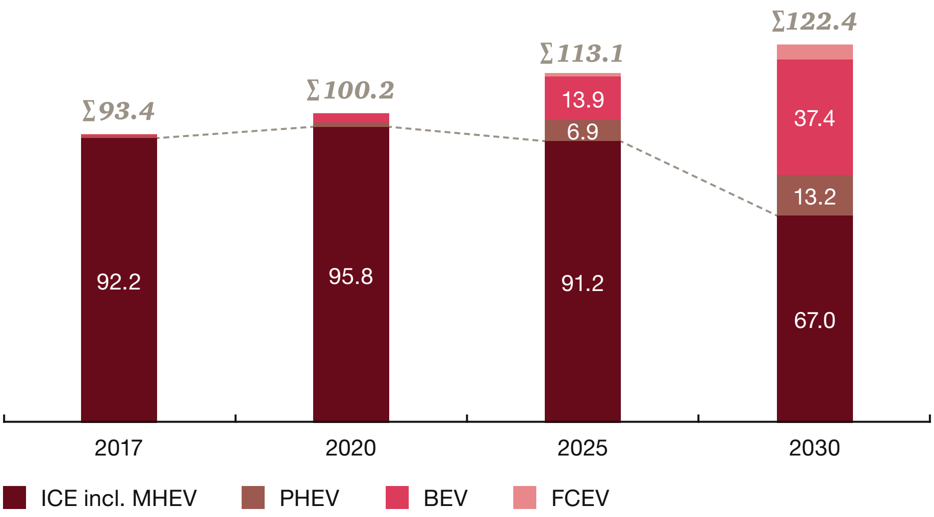
Powertrain production costs are lowest today for ICEs. Stricter regulations on CO_2 emissions will necessitate widespread adaption of expensive efficiency technologies, such as tribology optimization and 48V systems, while exhaust gas aftertreatment will further increase costs. BEV powertrains are well above ICE powertrain costs today, but will drop gradually, due to the ongoing decrease of battery cell prices and the economies of scale within the electric powertrain components. By 2030 we expect the BEV (still with a limited range of approx. 400km) and the ICE powertrain to be at the same level.

FCEVs will also benefit from the decreasing costs of the electric motors and power electronics. On the fuel cell side, mainly improvements of the processing technology of the stack and further industrialization will reduce costs, while the tank system will profit from technology advances and economies of scale of the production processes. Still, the cost level of the FCEV is expected to stay above the other options by approximately 50%.

With many new technologies, there comes a tipping point where public acceptance of the technology and adoption increases rapidly. We believe that point will be reached at about 2025 for BEVs (and to a smaller extent, for FCEVs), complemented by a rise in regulation restricting access to urban areas for ICEs.

Having analyzed the quantitative (TCO) and qualitative (Usability) development on our focused powertrains as well as the development of drivers towards a powertrain transformation, we next shift the focus to future market volumes and implications for private and public players.

Fig. 9 Estimation of global vehicle sales by powertrain type (in million vehicles per year)

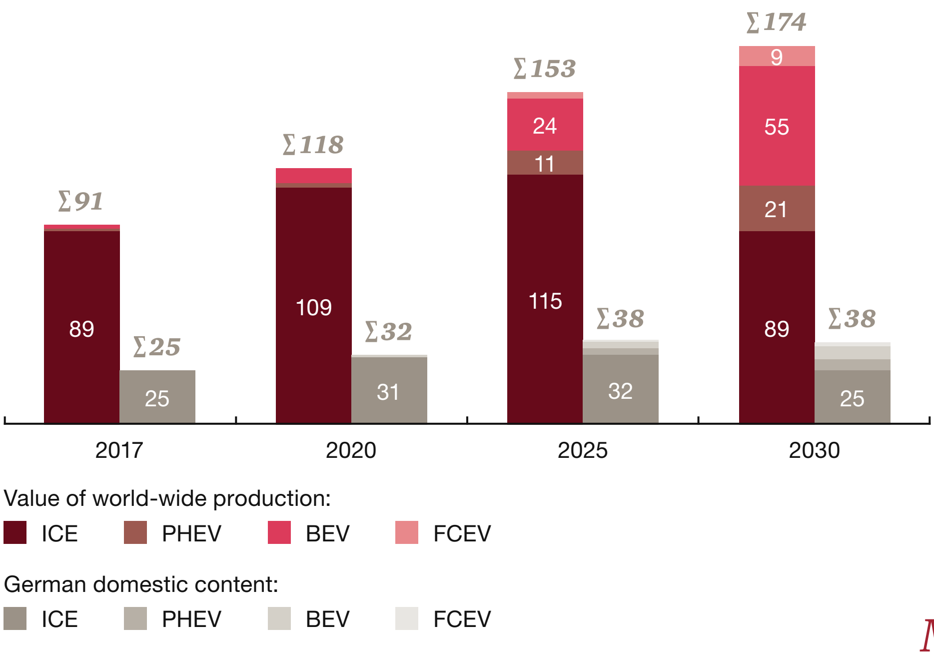


Our forecasts suggest that light vehicle sales will likely grow from 93 million units per year in 2017 to 122 million in 2030. While sales of vehicles with ICEs will increase over the next few years, beginning in 2020 they will start declining, with the rate of decrease accelerating over time. Over the same time period, PHEVs sales will slowly increase, while BEVs will grow strongly. In 2025, we estimate BEVs will make up 12% of the global sales, and 31% in 2030. We also expect FCEV sales to increase to 1 million in 2025 and ~5 million in 2030, mainly in the long-haul premium segment.

Although German OEMs have only few BEVs currently in their product portfolio, attractive models are in the pipeline. This enables them to not only participate in the short term growth of the market for conventional ICEs, but also in the emerging segments of PHEVs, BEVs, and FCEVs. The expected total market volume of German OEMs including their worldwide production, is depicted in Figure 10. It is expected to grow strongly from €91 billion in 2017 to about €174 billion in 2030.

The structure of the value chains and the respective localization on each level changes dramatically when comparing the emerging powertrain technologies.

Fig. 10 Market volume for powertrains produced by German OEMs worldwide and domestic content (in billion € per year)



For instance, the major part of the value of the battery, the most costly component of the BEV powertrain, is created non-domestically. Based on a model of the value chains and the localization on each level for all powertrains, the impact of the transition on the German domestic content is estimated.

The domestic content cannot keep the pace with the market volume. From 2025 on, we even expect it to stagnate, due to the large rise of the BEV segment. This is less dramatic for the OEMs, that profit from increasing production numbers and rely with their value creation not only on the mechanical parts of the powertrain. However, especially those suppliers that focus on ICE components to a large extent, will suffer from this development. From a national macroeconomic point of view, it means that the automotive industry in its entirety might reduce its importance in future, contributing less to the job market and overall macroeconomic performance.

Market share of ICEs will decline dynamically, especially from 2025 on.

ICEs will still remain largest segment in 2030.

E Time to act is now

0% of the automotive industry leaders think OEMs are well prepared for the upcoming transition.[2]

Over the last twenty years, the share of content developed and produced by OEMs has steadily declined. One area that's remained a core competency, though, is the internal combustion engine. As the overall market begins to shift towards BEVs, this core competency will lose some of its value. Beginning in 2025, the shift is likely to be more dramatic, as revenues from ICEs will begin to decline. Still, over the next few years, many companies should be able to generate strong profits from their ICEs. In our view, it's absolutely critical that they invest these in the new technologies that will drive the industry forward in the future. Given the low-level of maturity of BEVs and FCEVs, companies may be able to develop innovations that are truly unique (and potentially patent-able) to set them apart from the competition.

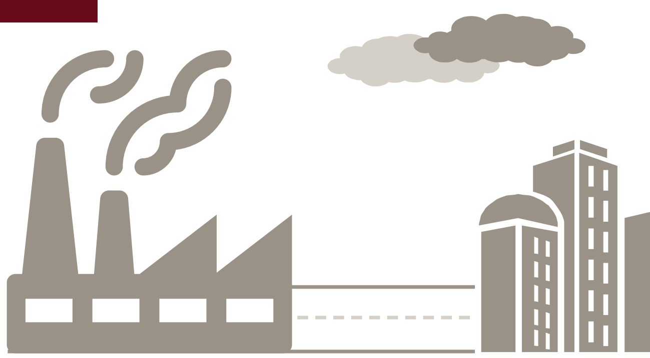
Recommendations for OEMs and suppliers:

- Revise product portfolio and technology roadmap
- Optimize products to ensure sufficient margins
- Industrialize the value chain appropriately for large scale production volumes
- Drive organizational change to reflect shift in technology

In our view, automotive OEMs and suppliers should take key strategic decisions very soon, including adjusting their product portfolio, improving product costs, optimizing the value chain, and driving organizational change.

The first step is adjusting the product portfolio. Companies need to be sure that they have the right types of vehicles for their target markets. Especially employing a purpose design for BEVs will be prerequisite to fill customer needs and to achieve competitive costs. They will also need to focus on some key technologies that enhance usability and streamline production. For example, wireless inductive charging could make an enormous difference, by freeing customers from the need to recharge at specific charging stations. There will be strong pressure to bring costs down on BEVs and PHEVs, so companies will need to optimize their products to ensure sufficient margins, e.g. by means of design-to-cost processes.

The next step will be for companies across the automotive industry to work together across the value chain. OEMs and suppliers should cooperate closely and work jointly to accelerate economies of scale and reduce costs. For OEMs, that should include taking care to avoid unnecessary cost drivers in their specifications to suppliers.



[2] PwC AutomotiveINNOVATIONS Conference 2017.

Perhaps most importantly, companies across the industry will need to drive far-reaching organizational change on a number of levels. They'll need to develop greater capabilities in electrical engineering. Organizational structures that have proven successful for conventional powertrains may not work as well for alternative powertrains, so it will be time to take a fresh look at how your company does things. For OEMs, that will include developing a strategy for how and where the future mix of powertrains should be produced. And with series roll-outs critical to consumer acceptance, research and pre-development will need to be closely connected to series engineering.

Mechanical and Plant Engineering Sector

The demand for mechanical parts and processes attributed with the ICE will reduce after 2025. At the same time a large buildup of production capacities and investments for new technologies is expected, leading to the following recommendations:

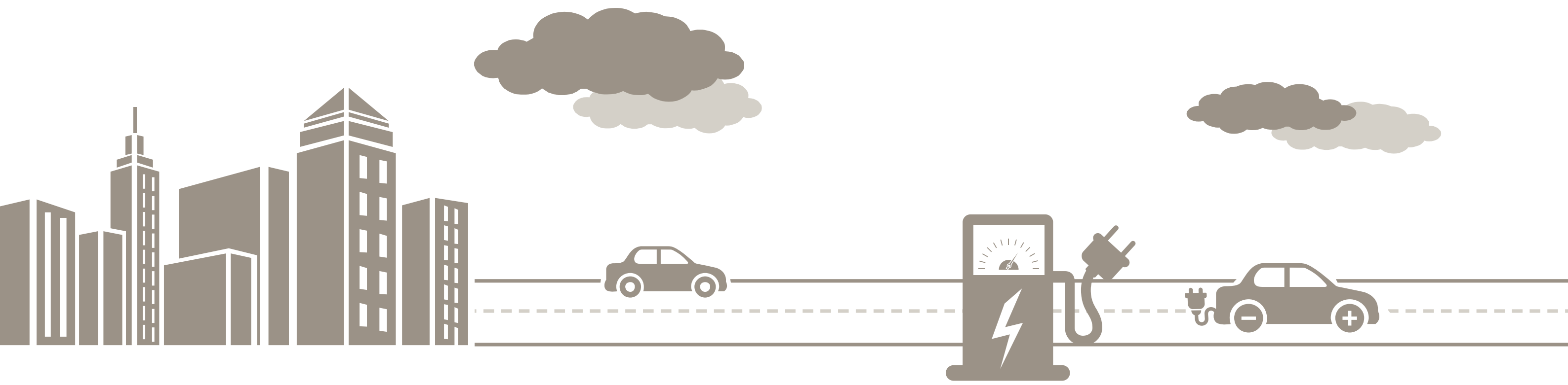
- **Adjust product portfolio**
  - Explore new products and technology trends for components together with potential customers
  - Apply existing and/or adjusted capabilities to improve manufacturing process in order to gain a selling proposition to the clients
- **Leverage global reach**
  - Enter and dominate new growing production equipment markets of alternative powertrain components
  - Improve and use global sales reach to maximize scale effects
  - Identify key global markets per component
- **Leverage industrial automation experience**
  - Apply existing production equipment capabilities with high standards of productivity and quality to new production processes
- **Broaden network**
  - Partner with other manufacturers of industrial machines to provide system solution
  - Engage in research networks and projects to improve manufacturing equipment and competiveness

Politics and Government

The transformation of fuels and powertrains will increase competition for OEMs resulting in risks and chances for the German domestic content and employment. Compliancy with emission reduction and clean air targets seems more feasible with the adoption of alternative powertrains. The independence of oil exporting countries will also grow.

Especially to avoid a negative impact on domestic content and employment the following actions are recommended:

- **Accelerate build-up of infrastructure**
  - Remove legal barriers for construction of private charging infrastructure
  - Directly invest in the build-up of public charging infrastructure and H_2 filling stations
  - Enable attractive market models for flexible load from BEVs
  - Check reduction of taxes and fees on electric power for BEVs
- **Education and research**
  - Enhance professional and academic teaching to ensure adequate qualification on all levels (e.g. engineering, production staff, service staff)
  - Increase research funding in all relevant fields (materials science and production technology of batteries, fuel cells, electric motors, power electronics, …)
- **Product and production technology**
  - Support local industry in installation of cell production line



F Wrap-Up

All players in the industry should prepare now for the ongoing transition and seek new business areas.

Growing concerns about negative effects of the climate change and raising awareness of local pollution are currently pushing the interest in alternative fuels and powertrains strongly. Taking CO_2 neutrality as a prerequisite and excluding biomass based fuels, renewable energy from wind and sun are the choice.

Different conversion paths are widely discussed but in a full supply scenario battery electric vehicles (BEVs) are advantageous in terms of energy efficiency, investments, and fuel costs. However, weak usability impedes widespread adoption of BEVs. In particular, range and refuel time fall short of the performance customers are used to from conventional vehicles. Key benefit for end users is the accessibility to zero-emission zones, which has an important impact on the sales of BEVs.

Hydrogen powered fuel cell electric vehicles (FCEVs) can combine the best of two worlds but costs and lacking infrastructure are critical issues. For special applications, such as long-range premium vehicles, FCEVs are still expected to become successful in the long run. Synfuels suffer from low efficiency and high cost but might be the only viable solution for applications with even higher energy demand such as long-haul heavy duty transport or aviation.

The main drivers of the transformation, such as local emissions and global warming, will lead to dynamic growth in global EV sales. In 2030, we expect a market share of 35% for EVs. However, sales of internal combustion engine powered vehicles (ICEs) will still represent the largest share throughout 2030.

OEMs and suppliers should act now and take strategic decisions soon. Adjustments in their product portfolios and technology roadmapping are key to ensure future competitiveness and profitability. By the industrialization of the whole value chain further cost reductions can be achieved.

For the mechanical and plant engineering sector, the large build-up of production capacities for new technologies generates opportunities as new machinery is needed.

Employment level and competitiveness of the national industry should be a main concern of the public sector. Governments have to deal with the risk of decreasing employment rates in the transition and should build a positive environment for the upcoming employment in future powertrains.

Readiness in technology and organization are key to be successful in the future.

Appendix

Detailed discussion of our conversion path methodology and assumptions

In the all-electric path, electricity is generated non-centralized in photovoltaic and wind energy power plants. An average loss of energy due to storage is estimated at about 6%, accounting for seasonal and time-variant supply and load, resulting in an efficiency of 94%. The distribution via the electrical grid on the transmission and distribution grid level is estimated at about 89% efficiency. From the charge plug to the wheel, an average efficiency of 84% is estimated, including losses during recharge of the BEV battery and actual use of the BEV.

Hydrogen gas as fuel is expected to be produced via electrolysis, splitting water molecules in hydrogen and oxygen gas. We expect de-centralized facilities, where electrolyzers are integrated in filling stations, to be the most economical solution for hydrogen supply. For the electrolysis and the storage of hydrogen gas at high pressure, we expect an efficiency of 69%. The distribution itself is covered by the electrical grid, distributing electric energy to the electrolyzers, at an efficiency of 95%. The total efficiency of the FCEV powertrain is expected to be at about 55%.

Synfuel is used as a collective term for synthetic hydrocarbons, produced from electrical power. As carbon source, CO_2 is used. We considered use of CO_2 from ambient atmosphere, as other CO_2 sources such as from steel production or biomass, are limited in their availability. All synfuels (and gaseous synthetic fuels, such as SNG) have in common, that in the first step hydrogen gas is produced from electric power by electrolysis. For the further processing, we assumed a "Carbon Oxides and Water to Liquid" (CWtL) process route, where hydrogen and CO_2 are processed to methanol. In a further step, methanol is then processed to a synthetic fuel with characteristics similar to diesel or gasoline fuel. The total efficiency including all processing steps is expected at about 44%. It should be noted that the processing is expected to be carried out in larger more centralized facilities than the production of hydrogen. Thus, we expect a higher efficiency of the electrolysis of 76%. The efficiencies for the CO_2 production from ambient air and the synfuel synthesis are assumed at 75% and 77%, respectively.

Other important routes for synfuels include diesel and gasoline fuels via the Fischer-Tropsch synthesis, and oxygen containing materials such as dimethyl ether (DME) and polyoxymethylene dimethyl ethers (PODE oder OME). These fuels were not considered here, due to their somewhat lower efficiency in production. However, the results described in the following for synfuels are expected to be fairly similar to what one would get from other synthetic fuels.

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