Roadmap zum defossilisierten Antrieb

Roadmap to a de-fossilized powertrain

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Abstract

The implementation of the Paris Climate Agreement requires a continuous reduction of greenhouse gas emissions by defossilizing our energy sources. For numerous countries throughout the world, it will be impossible to ramp up regenerative energy production by an order of magnitude needed to establish energy self-sufficiency in all sectors (power generation, industry, heating and transport). As a result, importing energy from regions with excess regenerative energy will be as commonplace as importing mineral oil today. For ease of worldwide energy transport, a chemical energy carrier seems very likely.

The transport sector has to achieve near-complete independence of fossil fuels by 2050 according to International Energy Agency models. In the long term, battery and fuel cell electric vehicles are essential pillars for decarbonizing the transport sector. Continuous improvement of vehicle efficiency and a strong increase of hybridization and electrification will lead to significant reductions in the required energy for the transport sector. Breakthroughs in battery and fuel cell technology and cost as well as the ramp-up of the charging/filling infrastructure are challenging but manageable. Where locally produced regenerative electrical power is available, electrified transport will be the preferred approach. However, parts of the transportation sector will rely on imported renewable energy and may require further powertrain solutions to avoid an additional energy conversion process. The decision on the right energy carrier is complex and incorporates various aspects beside efficiency such as technical feasibility; speed of implementation; and total investment cost for society, industry and individual end users.

While “efficiency defines technology” is the appropriate approach for limited available local regenerative energy, the “most economic business model” will decide on the future carrier for imported renewable energy. In this context, imported renewable synthetic fuels – as required for aviation and navigation – are a feasible candidate for heavy duty and passenger transportation.

1. Introduction

The Paris Climate Agreement (COP21) as entered into force Nov. 4th, 2016 is targeting to limit global average temperature increase to no more than +1.5 to +2 °C above the pre-industrial level. To achieve this challenging target a radical cut of fossil CO_2 emissions will be necessary reaching nearly net-zero (fossil) emissions around 2050. Achieving a 1.5°C scenario will require an 85 percent reduction compared to 2013 CO_2 emissions – yet substantially lower than the so far considered "2DS" scenario of the International Energy Agency (IEA) [1] (see figure 1). Significant reduction of CO_2 emissions will be very challenging for specific sectors. For example, agriculture and waste management are expected to demand approximately 2/3 of the remaining emission budget in Germany in 2050 [2]. The energy supply, industrial, residential and transportation sectors need to be nearly independent of fossil fuels, i.e. de-fossilized, by 2050. Alternative CO_2 emission reductions such as for example CCS (Carbon Capturing and Storage) might be useful as an intermediate solution, but compensate rather than mitigate the use of fossil energy. De-fossilization of the powertrain is therefore the long-term challenge.

2. Efficiency Potentials

Intelligent traffic systems including automated and connected driving as well as changing mobility behavior and increasing digitalization have the potential to reduce the primary energy demand within the transport sector. On the other hand, mobility demand is still increasing and might offset prior mentioned potentials as it did to some extent in the past. Reduction of direct vehicle related CO_2 emission is therefore crucial and will require actions at the vehicle level, on the powertrain and on the energy carriers needed for the propulsion.

2.1 Eco Innovations, Vehicle Measures and Engine Improvement

Increasing vehicle efficiency requires a holistic approach to the energy use on-board a vehicle. An increasing share of the energy demand is allocated by comfort features of the vehicle. To ensure reduced CO_2 emissions in real world driving conditions, intensive adoption of eco innovations will be required. Off-cycle credits – in Europe called eco innovations – are regulative measures that give credit for efficiency improvements of the vehicles beyond homologation procedure. Up to now sparsely used eco innovations like engine compartment encapsulation, solar roofs, navigation based operation strategies or coasting will gain more and more relevance in near future.

Curb weight, aerodynamic drag and rolling resistance are the decisive factors concerning the remaining energy demand for vehicle propulsion. Recent publications estimate the possible reduction of aerodynamic drag relative to a state-of-the-art vehicle as high as 25 percent [3]. Lightweight design and continuous advances on the vehicle's rolling resistance suggest that a 10 percent total reduction of energy required at the wheel could be achieved with future best in class vehicles compared to 2015.

The powertrain providing the energy to the wheels has potential for efficiency improvements as well. Downsized turbocharged ICE with direct injection have become the mainstream power source in the compact class. The introduction of Miller/Atkinson cycle engines in combination with advanced charging concepts for gasoline engines are a next step. Friction reduction, cylinder deactivation (even for 3-cylinder engines), high specific power concepts with electrical assisted boosting, maximized thermal efficiency concepts with high or variable compression ratios are additional technologies that are leading to the assumption of an additional power-train efficiency improvement of 10 percent based on a best in class engine configurations of 2015. The CO_2 reduction potential for a best in class vehicle (status 2015), with only engine improvements and vehicles measures and without usage of eco-innovations, may reach 15-20 percent in total by 2030. Since many vehicles do not

yet utilize all available best in class technologies, the average potential of engine and vehicle measures for new sales can be higher.
Even though the best technology to reduce the vehicles fuel consumption will have to stand its ground in the economic competition which is most challenging for small vehicle classes.
Significant efficiency increase beyond 15-20 percent will be achieved by increasing the implementation of electrification.

2.2 Electrification

High efficiency of an electric powertrain combined with the potential to recover energy from deceleration phases (recuperation) reduces the external energy needed for propulsion. For a combustion engine this results in lower fuel consumption (gasoline, diesel or gas). For fully electric vehicles (BEV and FCEV) less electric energy or hydrogen consumption is the consequence. For PHEV/REEV the CO_2 reduction potential in comparison to a high efficient ICE is related to the available battery capacity, real life charging behavior and as for BEV in particular to the CO_2 footprint of the local electricity mix.
Forecasts of BEV and FCEV electrification shares in passenger transportation for a period exceeding 5-10 years strongly depend on the assumptions for future development of key technologies (e.g. battery costs and raw material availability), end user acceptance of new technologies, national incentive programs, available infrastructure and future emission standards or city restrictions.
All efficiency measures reduce the need of primary energy. To achieve near net zero CO_2 emissions within the transport sector, the energy carrier itself will need to be fully independent of fossil energy sources (see figure 2). Renewable energy will not only be the basis for future transportation but also for all sectors. Energy transition (in Germany “Energiewende”) and especially security of energy supply become a long-term challenge.

3. Future Energy System (example Germany)

Renewable energies account for about 32 percent of the electric power generation and about 15 percent of the total end energy consumption for Germany in 2015. As of today, about 74 percent of the primary energy demand is based on imports. The energy system and distribution is diversified (coal, gas, oil, renewables) and provides more than 500 TWh of storage capacity (e.g. oil: 257 TWh, gas 210 TWh). Installed photovoltaic and wind power has reached about 90 GW in 2016.

Transition of such a diversified energy system into an energy system primarily based on local renewable energy sources and the electric grid for distribution is feasible and challenging at the same time. Due to strongly fluctuating solar and wind energy collection, extensive built-up of installed photovoltaic and wind power will be required as well as large investments in storage capacities and backup power plants. Related studies suggest that the necessary built-up of photovoltaic and wind power ranges from 325 GW to 540 GW [2,4]. At the same time, the primary energy demand needs to be halved by 2050 [2].

For its strong decarbonization scenario "95" (95 percent CO_2 reduction), a study conducted by Öko Institut and Fraunhofer [2] indicates an increase of the energy-only-market price for electricity up to 21,5 EURct/kWh in 2050 also due to necessary backup power plants (see figure 3). For reference: the average energy-only-market price was about 2,9 EURct/kWh in 2016. At the same time, the "95" scenario assumes 50 percent of the remaining needed fuel – primarily for aviation and navigation – to be synthetic fuels based on renewable energies. Due to economics, the synthetic fuels are expected to be produced partially abroad.

A central goal of energy transition scenarios is the reduction of energy imports. As potentials for local renewable energy is limited and costs for storage and distribution are high, extreme efficiency and direct use of electricity within all sectors is assumed to be the primary target. As efficiency of renewable energies in geographically preferential regions is higher (e.g. about 2.5 times for photovoltaic yield compared to Germany) the dedicated production of electricity based synthetic fuels should be considered as a supplement for the local renewable energy sources.

4. E-Fuels

Synthetic fuels based on renewable energy – so-called eFuels (see figure 4) - will be an important pillar for future fuel supply. Transportable and easy to store chemical energy carriers are beneficial to solve the target triangle of energy policy: environmental impact, economic viability and security of energy supply. Renewable electricity in geographical preferential regions dedicated for the production of synthetic fuels will be the basis for the large scale production of e-hydrogen. The e-hydrogen can be used for fuel cell vehicles or synthesized by additional conversion steps to synthetic methane (e-CH4) or synthetic fuels for an increasing blend in the remaining gasoline and diesel fleet, not only for aviation and navigation but also for commercial and passenger vehicles.
As electricity-based synthetic fuels are not relying on food stock nor special climate conditions the upscaling of production volume is nearly unlimited. Cost of electricity is the dominating factor for synthetic fuel production driven mainly by electrolysis and CO_2 capturing. With high yield photovoltaic plants already reaching energy costs per kWh below 3 USct in 2016 (Abu Dhabi 2,42 Ct, Chile 2,91 Ct) [5], synthetic fuels for direct use in existing car fleets (e.g. eMethan, eMethanol, eGasoline, eDiesel) are expected to reach a cost level of 10–15 EURct/kWh depending on the complexity of the energy carrier and available CO_2 source (see figure 5). For large scale industrialization, further technology development in the field of high temperature electrolysis and CO_2 capturing is necessary. Demonstration level pilot plants are already "online" today and industrialization is expected to be feasible within 5-10 years.

5. Economy of eFuel

At today's oil price, synthetic fuels are of higher costs than fossil fuel. Fossil fuels need to be replaced within the transport sector in the long term so eFuels will have to compete economically with alternative powertrain concepts such as battery electric vehicle. eFuel powered ICE vehicles are considered to be in co-existence with BEV and FCEV in the market. Though it is obvious that a transition to an alternative energy carrier such as battery or fuel cell electric vehicle will require a large additional investment in charging and refueling infrastructure, the additional invest in a nationwide new infrastructure is not yet considered at this time. The following comparison is based on a simplified end customer total cost of ownership (TCO) including only vehicle price and fuel costs. The basis for the comparison is a compact class vehicle with an end customer price of 30.000 EUR and best in class ICE technology. The expected end customer range for a battery electric vehicle in real driving conditions is app. 400 km and requires a battery capacity of approximately 70 kWh (15 kWh/100km, 90 percent usable battery swing). A best in class hybrid ICE is assumed to have a NEDC emission of 70g [6] and fuel consumption in real life condition of 4,2 liter/100km [7].

Vehicle manufacturer technology costs are derived by FEV [8] and the target year 2025 with powertrain costs for BEV of 8.900 EUR and ICE powertrain costs (incl. hybridization, exhaust measures, etc.) of 5.700 EUR.

A variation of 29-39 EURct/kWh for electricity price is used to represent uncertainties in electricity cost increases and surcharges for public charging.

Pricing of eFuels at the gas station has two major tuning factors: blend rate of eFuel and taxation - taking into account that electricity has a significantly lower tax contribution within the traffic sector. As of today, the tax contribution of a battery electric vehicle with a consumption of 20 kWh/100 km (incl. charging losses) is about 1,30 EUR/100km (electricity: 29 EURct/kWh). The tax contribution per 100 km of a 5L gasoline ICE is about 4,30 EUR (price: 1,33 EUR/Liter).

For the TCO comparison a 100 percent eFuel is considered with a market price variation of 2,0-2,5 EUR per liter representing a low and high taxation scenario. In order to be comparable in a well-to-wheel consideration with a BEV, a fossil-eFuel blend would still be justified resulting in lower fuel price at the gas station.
Due to the lower vehicle price of HEV, investment and running costs using even an 100 percent eFuel are more favorable up to 90-160 tkm depending on pricing of the specific energy carriers (see figure 6).

6. Climate Targets

Estimating how near-net-zero emissions could be reached by the European passenger car fleet by 2050 a long-term and energy-based scenario has been considered [9]. Development of the European passenger car fleet is based on new registration shares given by the 2-degree scenario model of IEA, constant EU28 fleet size of 250 million passenger cars and 16 million of them replaced every year. The qualitative projection yields that in 2050 about 60 percent of the vehicle fleet consists of high efficient hybrids, 36 million PHEV partially operating on ICE, and 55 million vehicles fully electrified. Including a constant volume of approximately 15 million tons of biofuels with increasing GHG reduction potential, well-to-wheel CO_2 emissions of the EU28 passenger car fleet result in a reduction of approximately 70 percent in 2050 compared to 2013. This estimate is consistent with the overall reduction target given by the IEA “2DS” scenario.
As the transport sector is targeted to achieve nearly net-zero emissions close to 2050 according to the Paris Agreement targets, de-fossilizing the remaining fuel becomes inevitable. To achieve near net-zero emissions of the EU28 passenger car fleet by 2050, additional synthetic fuels need to be brought into the market. With an assumed blend of 1 percent in 2025, 10 percent in 2030, 40 percent in 2040 and completely replacing the fossil fuel share by 2050 near net-zero emissions are

achievable. As eFuels will be introduced into the existing fleet, they have a direct and fast impact on the overall fleet emission (see figure 7). A drop below 200 million tons of yearly CO_2 emissions can be reached 12 years faster and accumulated savings of CO_2 emissions between 2025 and 2050 would total approximately 2.8 Gt, representing 3 times the overall emissions of Germany in 2014.

7. Summary / Roadmap

A key element for de-fossilizing the passenger car fleet by 2050 is the improved power-train efficiency to minimize the demand in overall primary energy. Electrified hybrids will likely replace “pure” ICE as mainstream before 2030.
With the built-up of charging infrastructure battery electric vehicles will gain significant market share with the high potential of becoming mainstream for urban mobility.
A complete transition of the entire EU passenger car fleet to battery electric vehicles might be restrained, e.g. by limitations in battery raw material supply. For long range applications we expect TCO competitiveness for battery electric vehicles, hybrid vehicles running on synthetic fuels and fuel-cell electric vehicles. All energy carriers (electricity, hydrogen and hydrocarbon fuels) will need to be de-fossilized by 2050. For countries with seasonally fluctuating renewable energy, a complete conversion to a 100 percent electricity-based energy system will be especially challenging and of high costs. Transportable and storable renewable energy carriers such as hydrogen or synthetic hydrocarbon fuels will help to limit the necessary investment costs for grid extension, storage and complementary power plants. For economic reasons these renewable energy carriers will be imported from geographically privileged regions.
The roadmap to a de-fossilized powertrain is therefore a threefold pathway including highly efficient hybridization, pure electrification and de-fossilization of the utilized fuels (see figure 8).

Literature

[1] World Energy Outlook, International Energy Agency, 2015

[2] Klimaschutzszenario 2050, 2. Endbericht, Öko-Institut, Fraunhofer ISI, 2015

[3] Automotive Aerodynamics in 2020, ATZ 12/2016

[4] Was kostet die Energiewende, Fraunhofer-Institut für Solare Energiesysteme ISE, 2015

[5] http://fortune.com/2016/09/19/world-record-solar-price-abu-dhabi/

[6] Review Of Combustion Engine Efficiency Improvements And The Role Of Sufficient Standardization, 14th International conference on renewable mobility

[7] From Laboratory to Road, White Paper, ICCT, Nov. 2016

[8] FEV Study partially published 12/2016, e.g. http://www.faz.net/aktuell/technik-motor/auto-verkehr/elektroautos-fordern-hersteller-und-zulieferer-heraus-14547766.html

[9] Roadmap zum de-fossilisierten Antrieb, Bosch, 17. Internationales Stuttgarter Symposium

Abbreviations

ICE Internal combustion engine

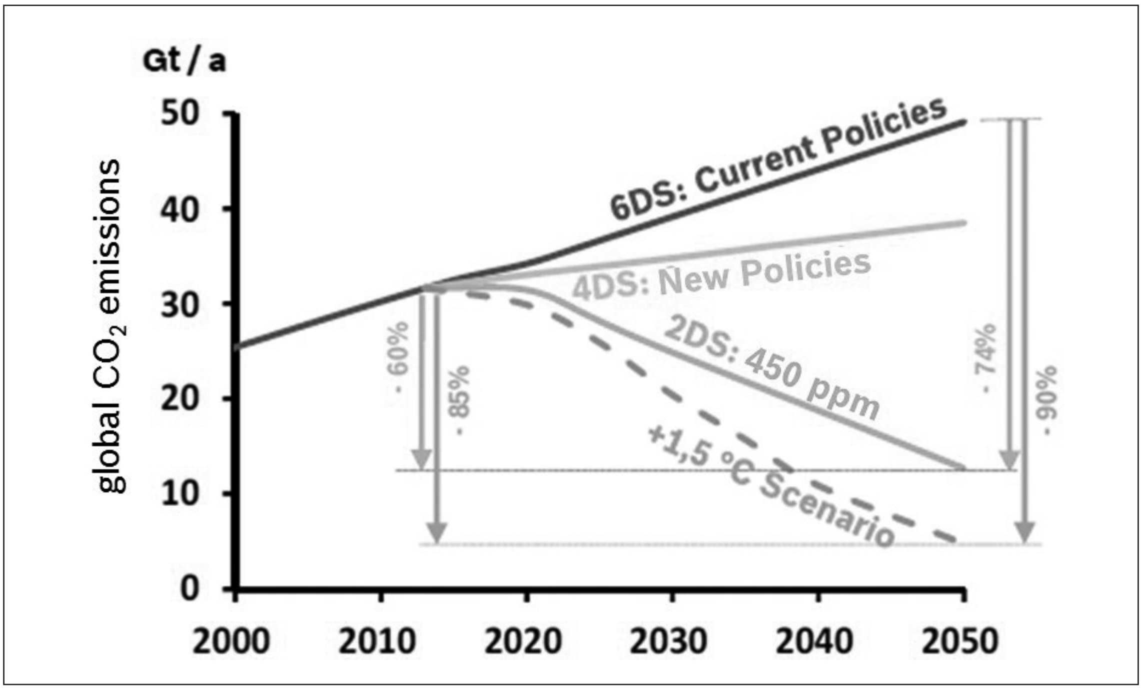
PHEV Plug-in hybrid electric vehicle

SHEV Strong hybrid electric vehicle

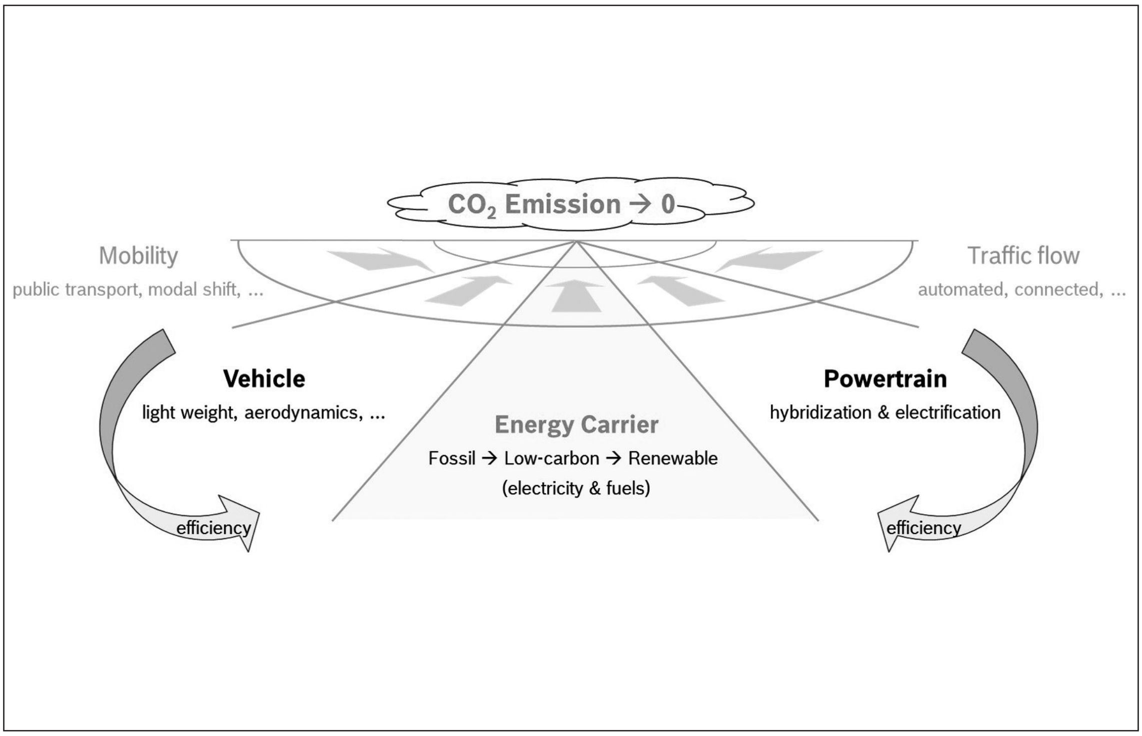
REEV Range-extended electric vehicle

FCEV Fuel-cell electric vehicle

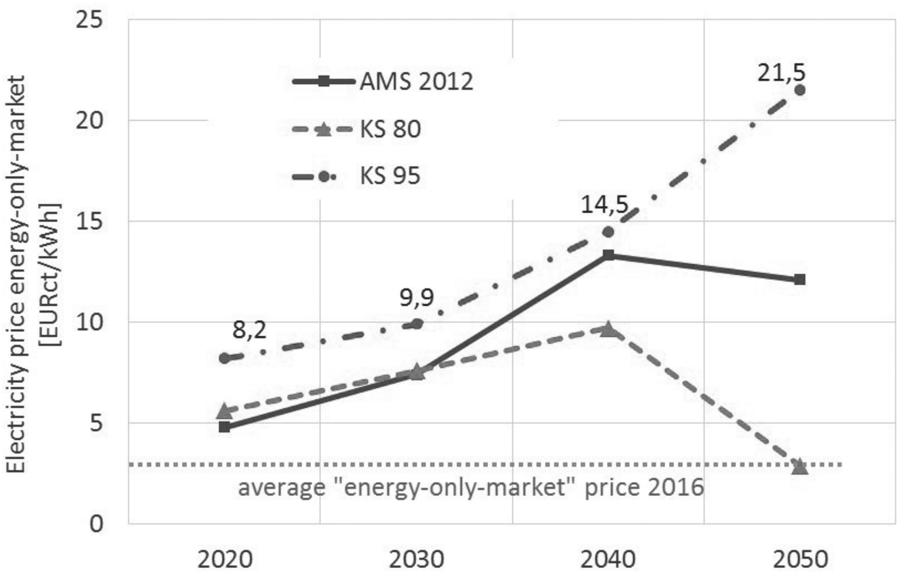
Picture Annex



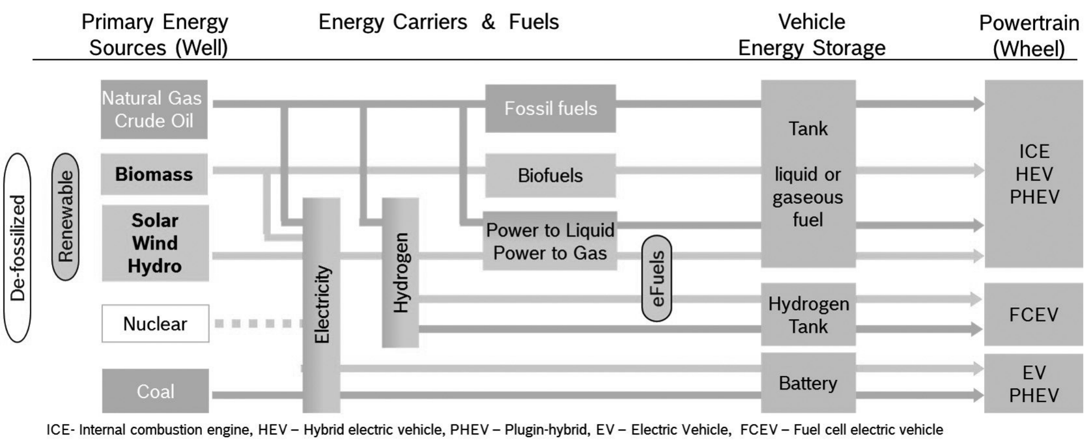
Global CO2 emissions for scenarios: IEA 2DS, 4DS, 6DS [2] and projected 1.5°C



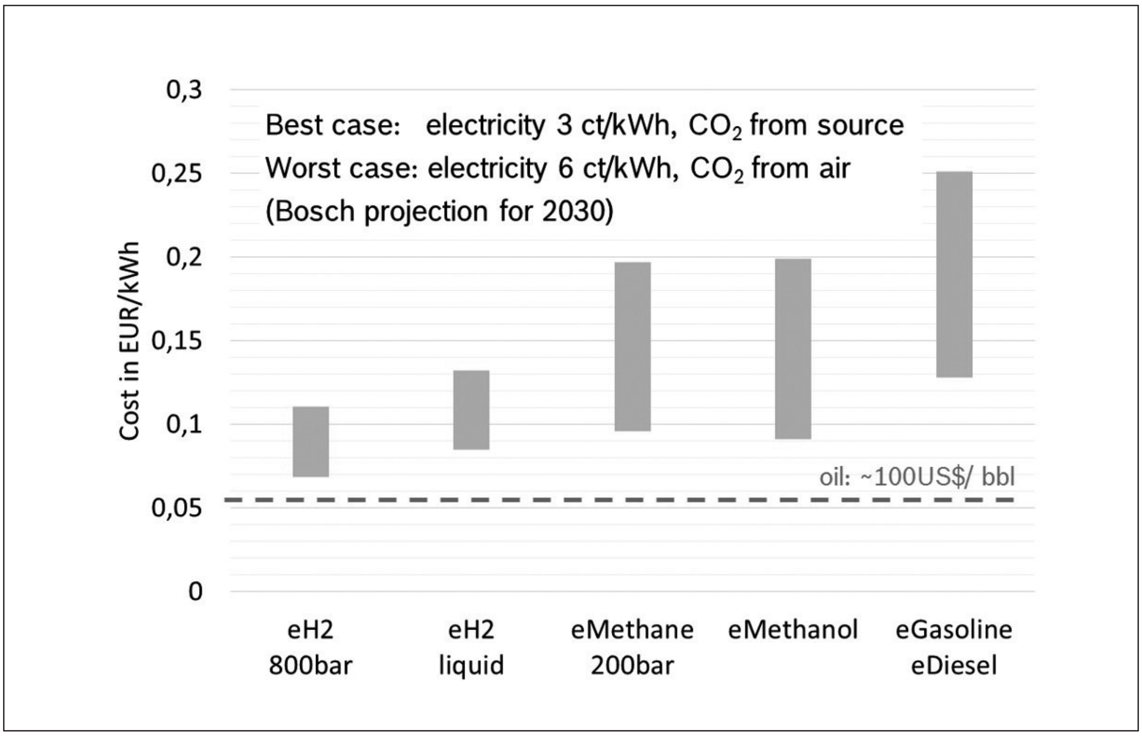
Fields of action for CO2 reduction of transport sector



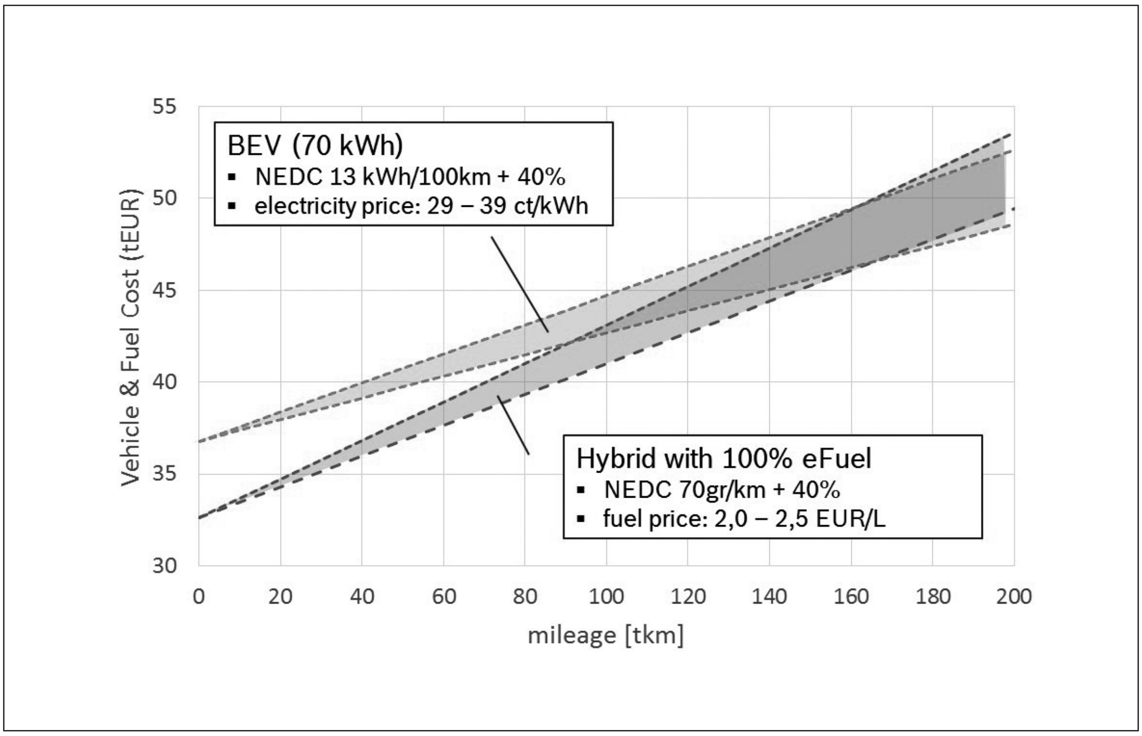
Energy-only-market price development [2]



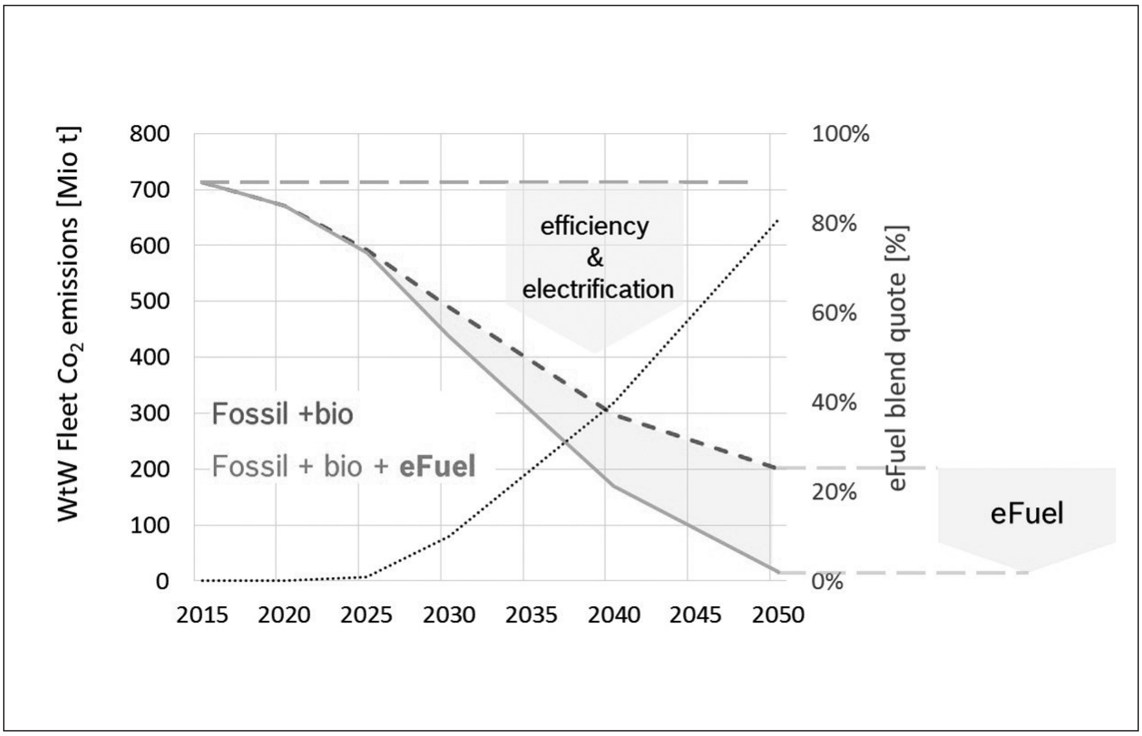
Definition of de-fossilized fuels and eFuels



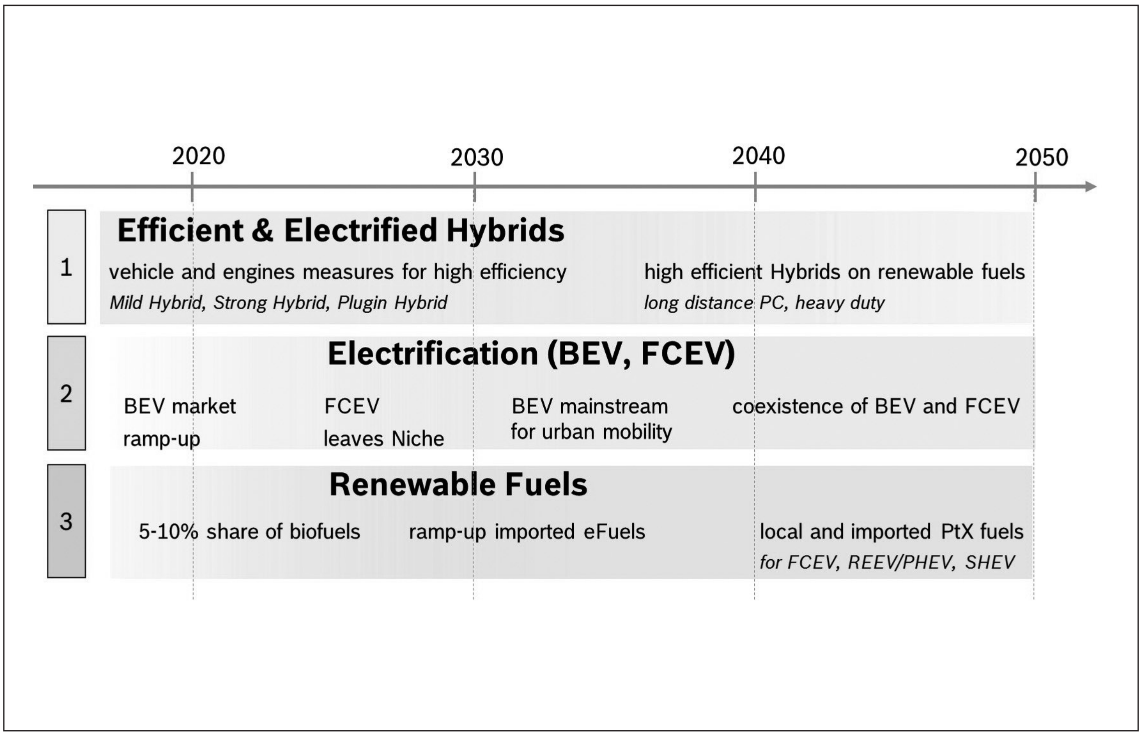
Projected cost ranges (best/worse case) for different eFuels ex refinery



Vehicle price and fuel cost of eFuel-HEV and BEV, compact class 2025



Qualitative projection of EU28 passenger car fleet CO2 emissions (WtW)

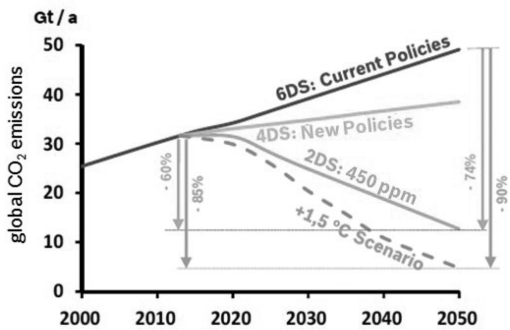


Threefold pathway to a de-fossilized powertrain

Roadmap to a de-fossilized Powertrain
Paris Agreement

PARIS2015 COP21·CMP11

▶ Paris Climate Agreement (COP21) entered into force Nov. 4th, 2016



▶ **Target**
Limit global average temperature increase to less than +1.5 to +2 °C vs. pre-industrial levels

▶ **Measure**:
Substantial cut of CO_2 emissions by 2050
Nearly net-zero emission for transport sector

2, 4, 6 DS: Scenarios resulting in app. 2,4,6 °C global warming, (based on International Energy Agency)

➢ Paris Agreement forces low carbon society and nearly net-zero Passenger Car CO_2 emissions by 2050

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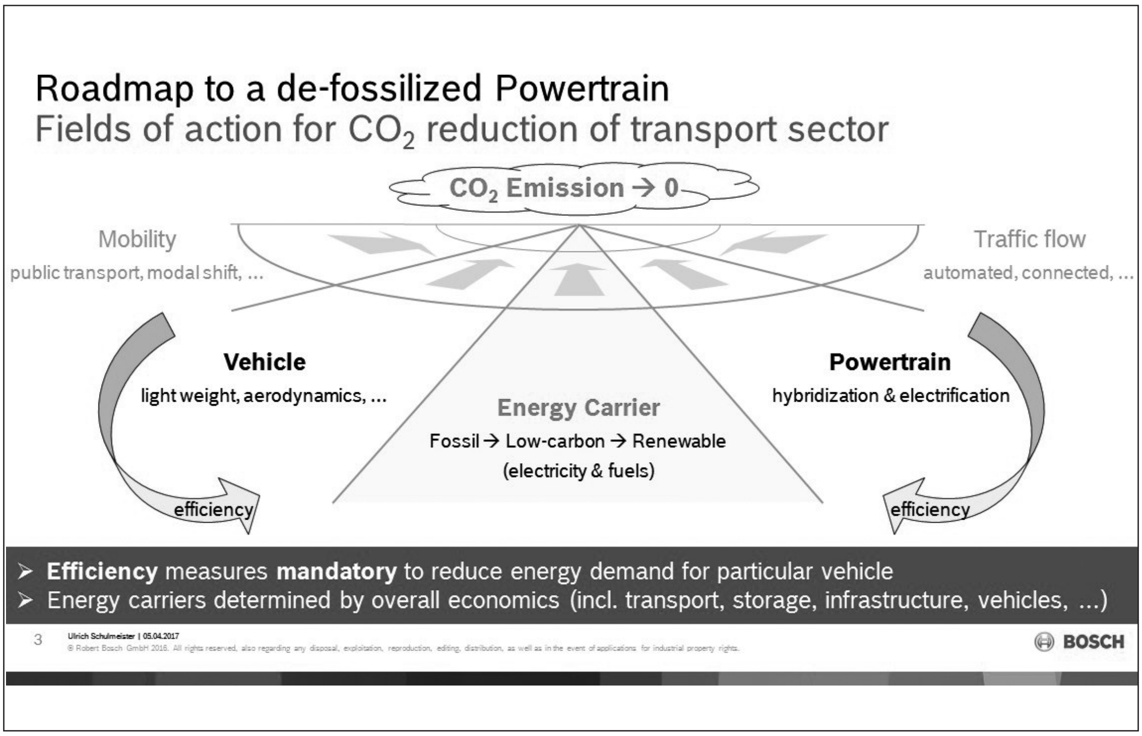
Roadmap to a de-fossilized Powertrain
Fields of action for CO_2 reduction of transport sector
CO_2 Emission → 0
Mobility
public transport, modal shift, …
Traffic flow
automated, connected, …
Vehicle
light weight, aerodynamics, …
Energy Carrier
Fossil → Low-carbon → Renewable
(electricity & fuels)
Powertrain
hybridization & electrification
efficiency
efficiency
➢ Efficiency measures mandatory to reduce energy demand for particular vehicle
➢ Energy carriers determined by overall economics (incl. transport, storage, infrastructure, vehicles, …)
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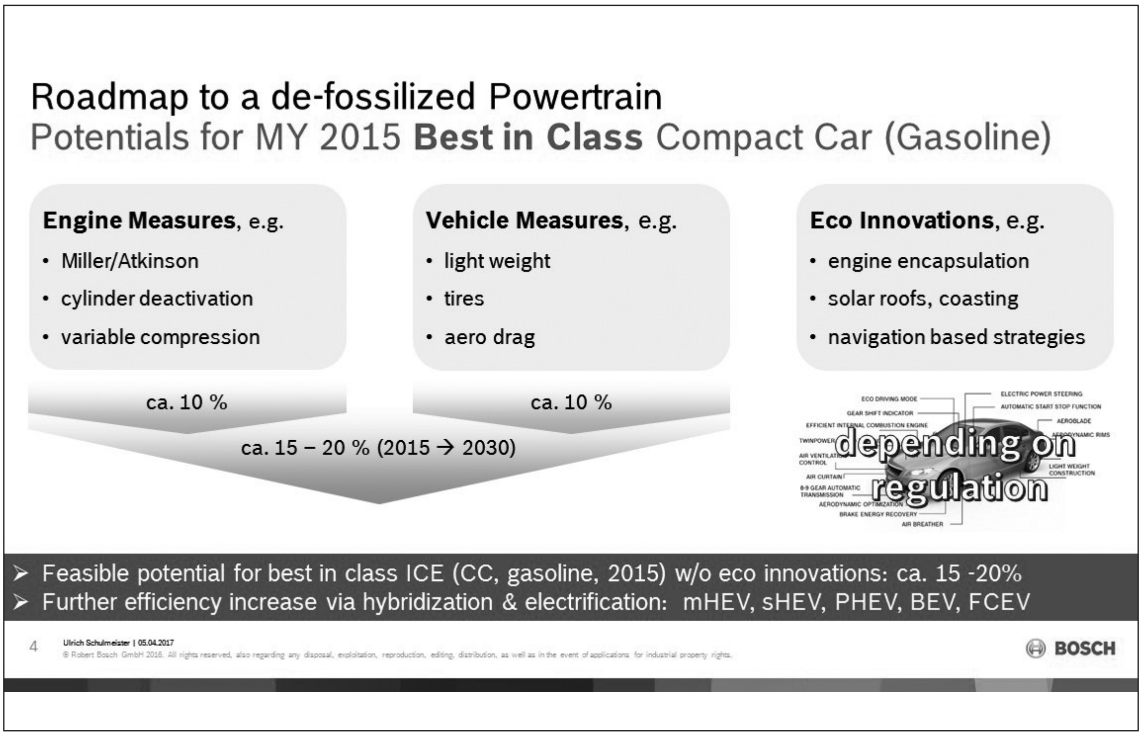
Roadmap to a de-fossilized Powertrain
Potentials for MY 2015 Best in Class Compact Car (Gasoline)
Engine Measures, e.g.
• Miller/Atkinson
• cylinder deactivation
• variable compression
Vehicle Measures, e.g.
• light weight
• tires
• aero drag
Eco Innovations, e.g.
• engine encapsulation
• solar roofs, coasting
• navigation based strategies
ca. 10 %
ca. 10 %
ca. 15 – 20 % (2015 → 2030)
depending on regulation
➢ Feasible potential for best in class ICE (CC, gasoline, 2015) w/o eco innovations: ca. 15 -20%
➢ Further efficiency increase via hybridization & electrification: mHEV, sHEV, PHEV, BEV, FCEV
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Roadmap to a de-fossilized Powertrain
Hybridization & Electrification (Passenger Cars)

	Mild Hybrid	Strong Hybrid	Plug-In Hybrid	REEV	BEV	FCEV
Electric Power[1]	5 – 20 kW	30 – 100 kW	40 – 140 kW	60 – 160 kW	60 – 300 kW	60 – 300 kW
	Brake energy recuperation	Limited electric driving range	50-100 km electric driving w/o restrictions	electric driving with "Range Extender" (RE)	Zero emission driving w/ regenerative energies	Zero emission driving w/ regenerative energies
CO_2 Reduction (Tank to Wheel)	10-15%	15-25%	40-60% *	50-90% *	100%	100%

* depending on battery capacity and charging profile

➢ Well-to-wheel CO_2 reduction potential of PHEV, REEV and BEV dependent on local electricity mix

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[1] indicative values

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Roadmap to a de-fossilized Powertrain
Future Energy System (e.g. Germany)

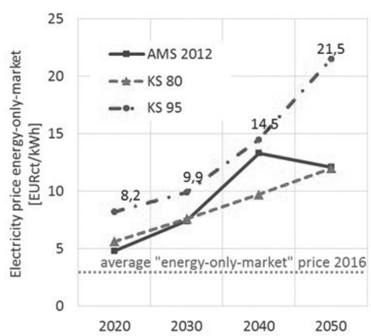
Energy System 2016

- Energy import: 74 %
- Fuel diversity: coal, gas, oil, electricity
- Storage >> 500 TWh (257 TWh oil, 210 TWh gas)
- Photovoltaic + Wind: ~ 90 GW
- Power plants: ~ 100 GW (conventional)

Energy System 2050 (plan)

- Target: ~ energy autarchy (< 20% import)
- High dependency on electricity
- Limited storage potential
- Photovoltaic + Wind: 325-540 GW [1)]
- Backup power plants: 70-130 GW [1)]

Energy-only-market electricity price [2)]



[2)] Klimaschutzszenario 2050, 2. Endbericht, Öko-Institut, Fraunhofer ISI, 2015

➢ **Energy autarchy** mainly based on electricity: **theoretically feasible** but w/ very high invest
➢ Additional transportable & storable renewable energy carrier necessary – likely as import

[1)] depending on study: Klimaschutzszenario 2050[2)] – Fraunhofer ISE 2015: „ Was kostet die Energiewende?"

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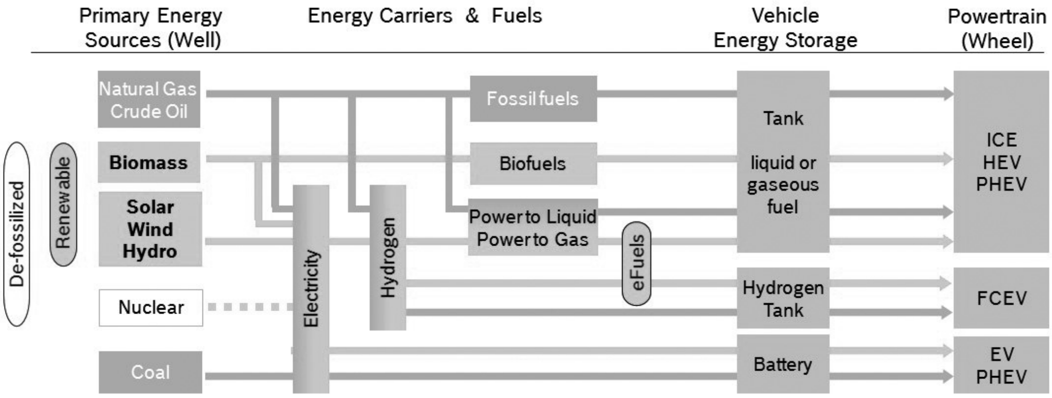
Roadmap to a de-fossilized Powertrain
Definition of eFuels



ICE- Internal combustion engine, HEV – Hybrid electric vehicle, PHEV – Plugin-hybrid, EV – Electric Vehicle, FCEV – Fuel cell electric vehicle

➢ eFuels: synthetic fuels based on renewables energies, e.g. eH2, eCH4, eDME, eGasoline/eDiesel, …

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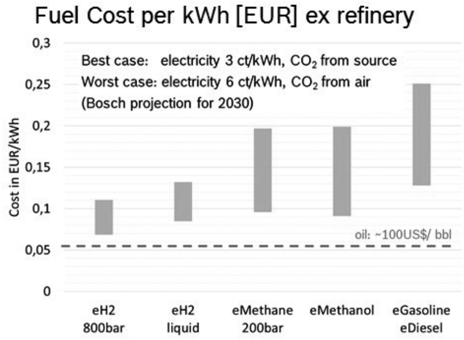
Roadmap to a de-fossilized Powertrain
Status eFuels

- eFuel costs mainly determined by electricity costs
  - Photovoltaic already < 3 USCt/kWh (Dubai, Chile, 2016)
- Hydrocarbons (e.g. eCH4, eGasoline/eDiesel)
  - additional costs for carbon source
  - but suitable for drop-in (fleet, infrastructure)
- Unlimited upscaling (not feed stock based)
- Maturity level: pilot plants

Fuel Cost per kWh [EUR] ex refinery



➢ Large scale industrialization feasible within 5-10 years
➢ Regulation push necessary to drive further invest in R&D and industrialization

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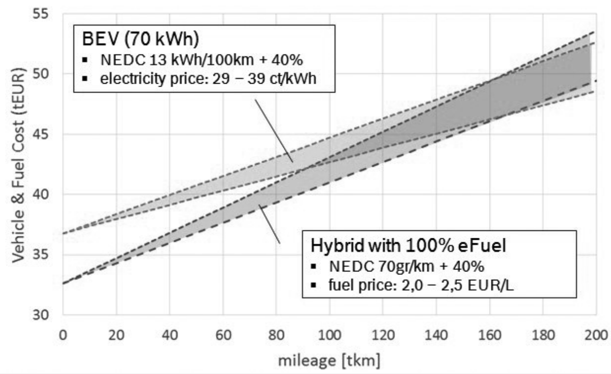
Roadmap to a de-fossilized Powertrain
Total Cost of Ownership (Vehicle + Fuel), Compact Car 2025



- ▶ Baseline: „best in class" compact car 2016
  - Market price: ~ 30.000 EUR
- ▶ Assumption: Powertrain costs (**FEV data**)
  - ICE 2016: 4.400 EUR (incl. gear)
  - Hybrid 2025 5.700 EUR
  - BEV 2025 8.900 EUR (70 kWh)
- ▶ Assumption: OEM integration costs
  - Powertrain integration costs BEV = 75% ICE

➢ Break-even eFuel-HEV with BEV between 90 – 160 tkm, taxation of eFuel decisive
➢ Tax yield / 100 km: **ICE ~ 4,3 EUR** (5L w/ 1,33 EUR/L) - **BEV: 1,3 EUR** (20 kWh @ 29ct/kWh)

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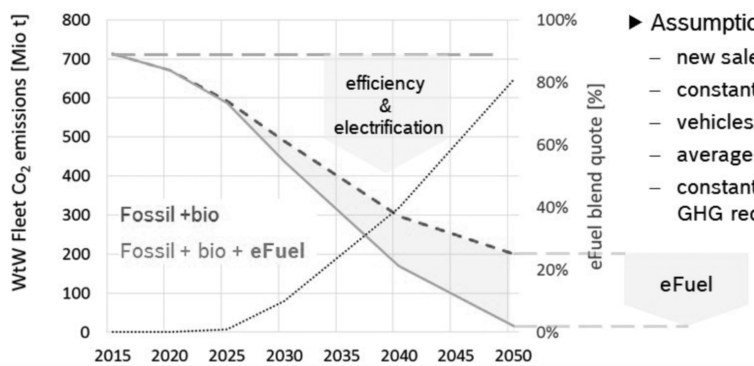
Roadmap to a de-fossilized Powertrain
Projection: Well-to-Wheel CO_2 Emissions EU28 (Passenger Cars)



- ▶ Assumptions
  - new sales according to IEA 2 DS scenario
  - constant passenger car fleet 253 Mio.
  - vehicles out of market after 15 years
  - average annual mileage 14.000 km
  - constant biofuel volume w/ increasing GHG reduction potential

2015: ~ 250 Miot fossil fuel
2050: ~ 65 Mio t eFuel

➢ eFuels necessary to achieve de-fossilization of EU28 passenger car fleet by 2050
➢ 2025-2050 accumulated CO_2 savings by eFuel blend-in: ~ 2.8 Gt (total DE emissions 2016: 0.9 Gt)

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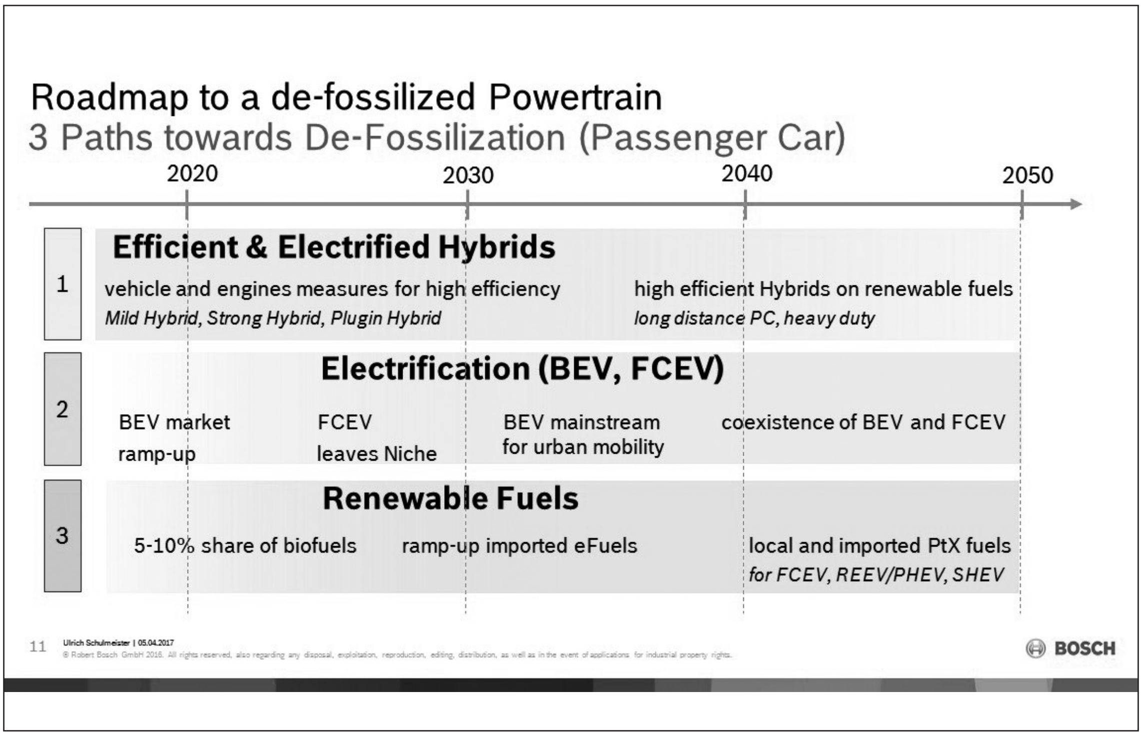
Roadmap to a de-fossilized Powertrain
3 Paths towards De-Fossilization (Passenger Car)
2020
2030
2040
2050
1
Efficient & Electrified Hybrids
vehicle and engines measures for high efficiency
Mild Hybrid, Strong Hybrid, Plugin Hybrid
high efficient Hybrids on renewable fuels
long distance PC, heavy duty
2
Electrification (BEV, FCEV)
BEV market ramp-up
FCEV leaves Niche
BEV mainstream for urban mobility
coexistence of BEV and FCEV
3
Renewable Fuels
5-10% share of biofuels
ramp-up imported eFuels
local and imported PtX fuels
for FCEV, REEV/PHEV, SHEV
11
Ulrich Schulmeister | 05.04.2017
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