# Energy Paths for Road Transport in the Future

A variety of technological options are available for climate-neutral road traffic. In a study, the Research Association for Internal Combustion Engines investigated the costs for several combinations of energy sources and powertrain systems on the basis of well-founded technical analyses. The results of the study show that synthetic e-fuels can be competitive, irrespective of their less favorable efficiencies across the entire energy chain.

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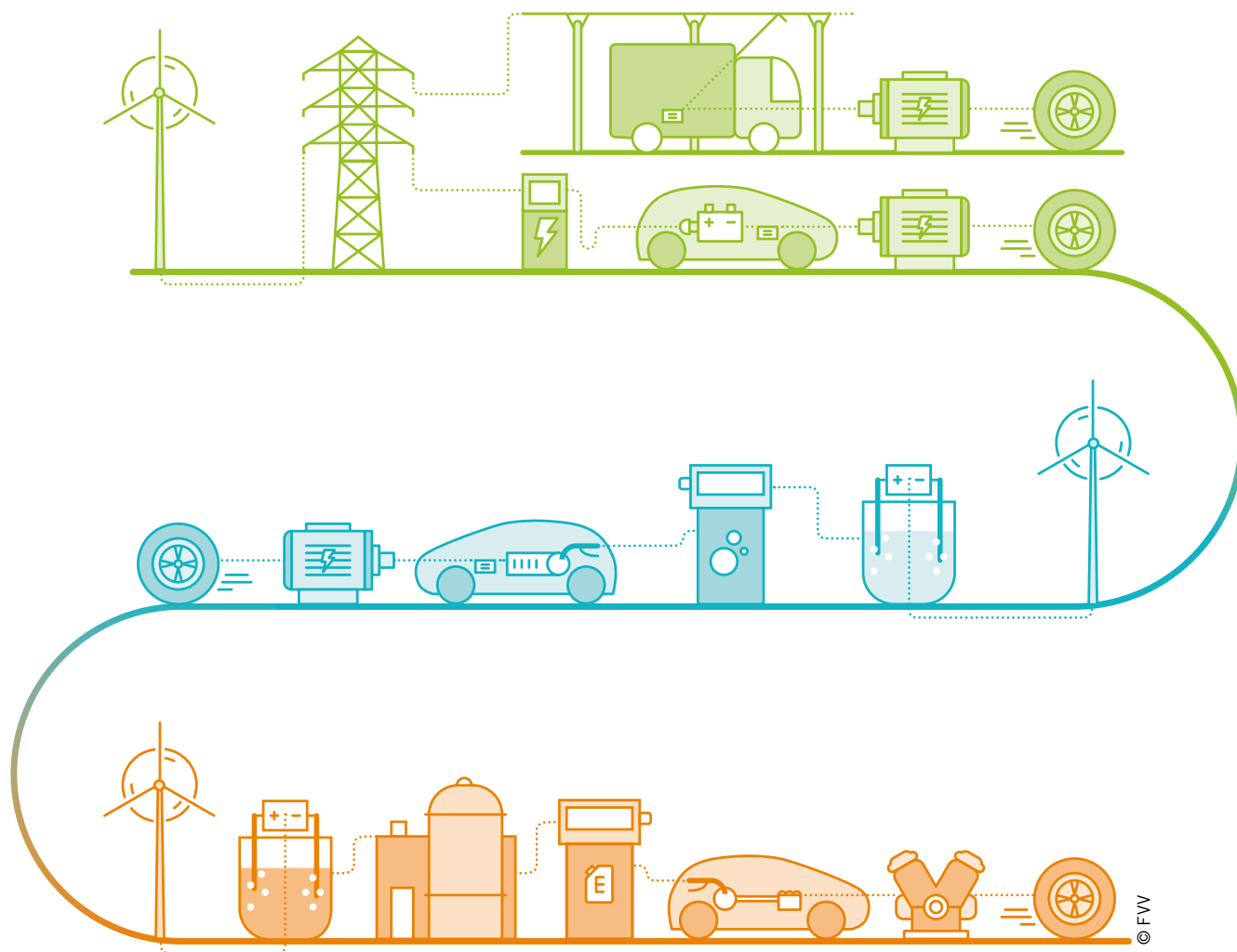
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MOTIVATION AND METHOD

The European Union's objective is to reduce greenhouse gas emissions by 80 % by 2050 compared with 1990 levels. Moreover, some member states such as Germany have committed themselves in their climate protection plan to reduce greenhouse gases emissions by 95 % over the same period. Against this background, a working group of the Research Association for Internal Combustion Engines (FVV) has analyzed in a comprehensive peer study different energy paths suitable for achieving climate-neutral road transport by the year 2050 along with the economic costs associated with the various paths. Therefore a technology-neutral approach has deliberately been chosen that takes into account three possible combinations of energy carriers and powertrain systems, **FIGURE 1**: direct usage in battery electric vehicles (cars or overhead-line trucks) powered by renewable electricity, fuel cell electric vehicles powered by hydrogen, and internal combustion engine vehicles powered by e-fuels, also known as Power-to-X (PtX) fuels.

In order to compare the economic implications of each energy path, the method used in the study consciously employs 100 % scenarios. This does not mean that a 100 % changeover to a single path appears realistic or desirable, but simply serves the purpose of better modeling. Due to the methodological approach chosen, the use of biomass-based fuels was intentionally excluded. Even though these alternative fuels can help to reduce CO_2 emissions from the transportation sector in the future, a complete substitution of fossil fuels with biofuels is far from realistic. The starting point for all the energy paths considered is a complete conversion of the electricity sector to renewable energy. An earlier FVV study has already shown that this is possible even if the demand for electricity increases significantly as a result of additional demand from the transportation sector [1].

In order to compare the costs for each energy path, the study looks at the mobility costs per km for light-duty passenger cars and medium and heavy-duty commercial vehicles respectively. The mobility costs include the costs for the production and distribution of the energy carrier as well as the depreciation costs for the acquisition of the vehicle. However, other expenses are not taken into account, in particular vehicle maintenance costs, taxes and insurance, which in reality make up a significant proportion of the operating costs.

INPUT PARAMETERS

Each of the 100 % scenarios has its specific boundary conditions that must be taken into account in an economic analysis, **TABLE 1**. For example, a complete switch to battery electric mobility requires continuous power generation. According to [2], a 20 % reconversion rate from PtX plants needs to be considered, when so-called dark doldrums – periods in which weather conditions prevent the production of solar or wind power – have to be compensated. With regard to the fuel cell scenario, we have to distinguish between centralized and decentralized (local) hydrogen production. With local production at the filling station, it must be assumed that neither electricity nor hydrogen can be stored on site to a reasonable extent, so that a
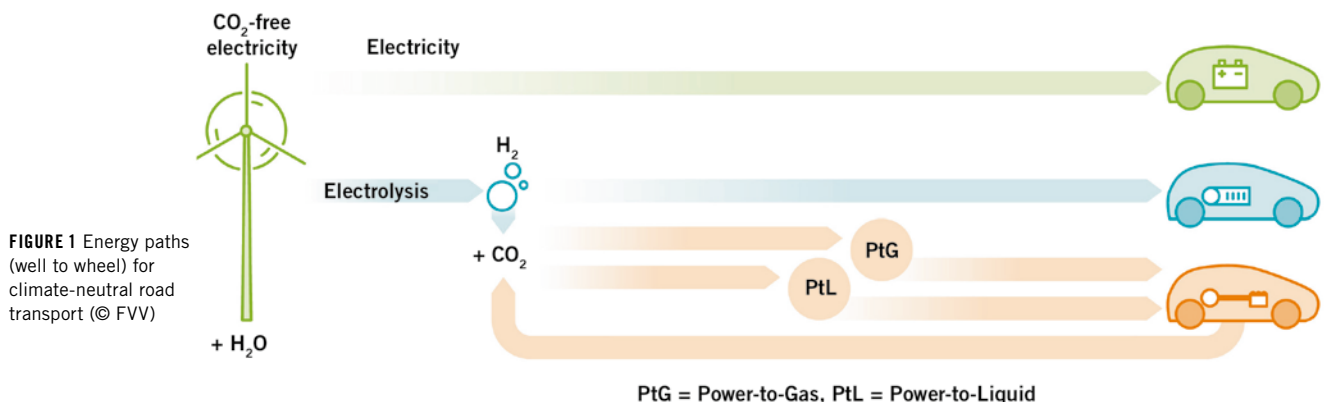

FIGURE 1 Energy paths (well to wheel) for climate-neutral road transport (© FVV)

PtG = Power-to-Gas, PtL = Power-to-Liquid

TABLE 1 Framework conditions for fuel/powertrain combinations (© FVV)

Fuel	Powertrain	Electricity supply	Energy storage	Energy distribution
Electricity (benchmark)	Battery Electric Vehicle (BEV)	Permanently available electrical energy, Germany	20 % energy buffer Pt-CH$_4$, reconversion for buffering during dark doldrums	Electricity distribution grid, Germany
E-H$_2$ (pressure tank in vehicle; local production at the filling station)	Fuel cell (FCEV)	Permanently available electrical energy, Germany	20 % energy buffer Pt-CH$_4$, reconversion for buffering during dark doldrums	Electricity distribution grid, Germany
E-H$_2$ (pressure tank in vehicle; central production, liquefied for transport)	Fuel cell (FCEV)	Intermittent electricity supply (fuel only produced when solar/wind power is available)	No additional energy storage. Energy storage for dark doldrums in the fuel itself; surplus production when solar/wind power is available	Local liquefaction for CH$_4$ and H$_2$
E-methane (vehicle: pressure tank)	SI engine ($\lambda = 1$)	Minimum cost scenario: production in MENA* (2030)		Transport of liquid fuel by ship (from MENA)
E-methane (car: pressure tank, truck > 3.5 t: liquefied methane (LNG)	SI engine ($\lambda = 1$) HPDI CI engine (> 3.5 t)	Maximum cost scenario: production in Germany (2017)		+ 500 km truck transport in Germany (for fuel from MENA and Germany)
E-methanol (MlOO)	SI engine ($\lambda = 1$)			
E-gasoline (Fischer-Tropsch)	SI engine ($\lambda = 1$)			
E-propane (LPG) (Fischer-Tropsch)	SI engine ($\lambda = 1$)			
E-diesel (Fischer-Tropsch)	CI engine			
E-OME	CI engine			
E-DME	CI engine			

*MENA = Middle East North Africa

reconversion rate of the same magnitude has to be considered. Centrally produced hydrogen and e-fuels, on the other hand, can be generated and stored in sufficient quantities for a two-week dark period. The study considers a total of eight different fuel/powertrain combinations, as several hydrocarbons have been discussed as energy sources for electric fuels so far. Only the Fischer-Tropsch (FT) process implies the simultaneous production of different fuels in the subsequent refining process. To take an economic view on the different energy paths, two cost scenarios are introduced: The maximum cost scenario, on the one hand, resulting from the combination of the most unfavorable parameters, and, on the other hand, the minimum cost scenario derived from the combination of the most advantageous parameters.

In order to calculate the primary energy demand, fuel consumption in Germany in 2015 is first converted into a mechanical energy requirement at the vehicle wheel (wheel energy requirement) using the known efficiencies of existing fuel/powertrain systems, **FIGURE 2**. For the sake of comparability, all possible external effects such as increasing demand

in freight transport are eliminated. Irrespective of efficiencies, each path considered must therefore provide 143 TWh of mechanical energy.

The costs of producing the energy carriers are essentially determined by the electricity costs. For intermittent renewable power supply from PtX processes, the maximum cost scenario is based on today's power supply costs of offshore wind turbines in the North Sea of 88.10 euros/MWh, while the minimum cost scenario assumes production in the MENA (Middle East and North Africa) region in 2030 at 24.26 euros/MWh. However, the costs of constant power supply required by the battery electric and locally produced (decentralized) hydrogen paths are expected to range between 100 and 180 euros/MWh. These costs consider both the costs and the degrading efficiency effect of the Power-to-Gas (PtG) production and gas-fired power plants required to bridge power failure in dark periods. A depreciation period of 20 years is assumed for the installations needed in the subsequent process steps – electrolysis, PtX synthesis including CO$_2$ separation and liquefaction. A full cost calculation must however take into account a whole series

of further assumptions, such as utilized capacities, start-up times and the efficiencies of various installations and process steps. These are detailed in [3].

Investments in the energy distribution channels, on the other hand, are largely dependent on the number and unit costs of charging points or filling stations. The minimum cost scenario considers a supply of 5000 full-fledged car filling stations – equivalent to 40,000 filling points – and 6000 additional filling points for trucks to be sufficient for all e-fuels and hydrogen. The 100 % battery electric scenario requires a minimum of 80,000 public fast charging stations and 17.5 million AC charging points at home and at work. As for the maximum cost scenario, these figures are doubled. Additional investments are required for the installation of overhead contact lines needed to electrify long-distance freight transport (electric highways). The minimum scenario, according to [4], is based on the assumption that 4000 km of federal freeways need to be equipped with overhead lines, while in the maximum scenario the entire German freeway network with a length of about 13,000 km is to be electrified due to the chosen methodical approach. The extent to

which the electricity grids need to be upgraded and expanded for a complete switchover to battery electric mobility, however, depends to a large extent on whether time-controlled charging is technically possible and accepted by the customer. In the best case – meaning charging times follow the energy supply, no (ultra-)fast charging and no balancing of peak loads for example at the start of holidays – the experts assume that no network expansion is necessary. In the worst case, an additional 77 billion euros need to be invested into expansion of the electricity grid, assuming a depreciation period of 40 years.
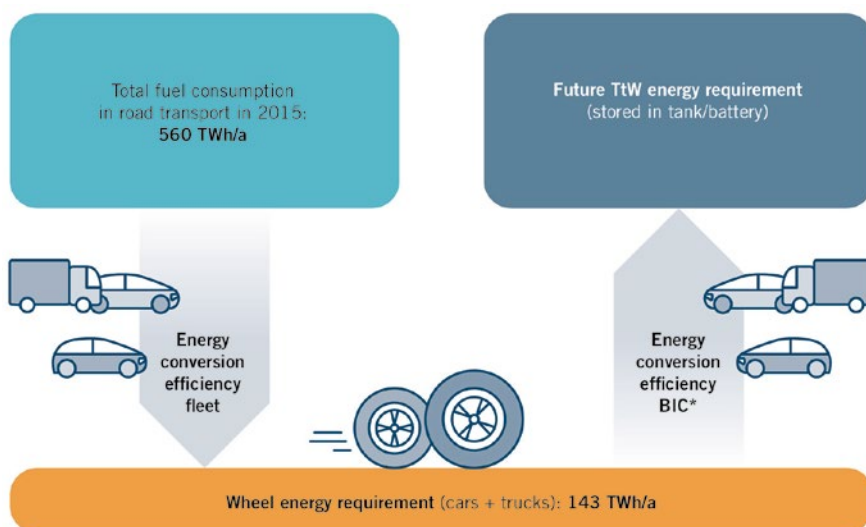
For competitive reasons, the cost of purchasing a passenger car is set at a flat rate of 20,000 euros for a model from the compact vehicle segment powered by a gasoline Spark-ignition (SI) engine. Based on current price lists, the extra charge for a comparable Compression-ignition (CI) engined diesel vehicle is 2400 euros. For the minimum cost scenario, the experts assume that fuel cell and battery electric vehicles will be at the same cost level as diesel vehicles in the future. For the maximum cost scenario, values from several sources are considered. The additional costs of up to 11,300 euros for a battery electric car with a nominal range of 500 km and 12,500 euros for a fuel cell vehicle are based on forecasts for 2030 according to [5].

The assumed depreciation period for vehicle costs is four years.

The purchase costs for trucks are calculated from the average of the prices of various CI engine-driven commercial vehicles available today, which is 90,400 euros. The extra charge for full electrification, including the pantograph power collector for overhead line operation on electric highways, was estimated at 52,000 to 87,500 euros. Additional costs of 36,500 to 125,000 euros are to be assumed for a fuel cell powertrain system. And a conversion to methane produced from renewable sources will cost between 14,000 and 24,000 euros, depending on the combustion process.

RESULTS: ENERGY REQUIREMENTS

The future energy requirement is decisive for all cost components except vehicle acquisition costs. To begin with, it can be derived from the required mechanical energy to power the wheels and the overall efficiency of the respective powertrain system. The very high efficiency of a battery electric vehicle leads to an annual Tank-to-Wheel (TtW) energy requirement of 176 TWh/a, assuming a constant vehicle population. A 100 % fuel cell fleet, however, has a significantly higher TtW energy requirement of 307 TWh/a. For the e-fuels considered in the study, the future TtW energy requirement ranges from 431 to

Total fuel consumption in road transport in 2015: 560 TWh/a

Energy conversion efficiency fleet

Future TtW energy requirement (stored in tank/battery)

Energy conversion efficiency BIC*

Wheel energy requirement (cars + trucks): 143 TWh/a

* BIC (best in class): car – most efficient compact-segment vehicle 2017; truck – degree of efficiency up to 43 %

FIGURE 2 Determination of the mechanical energy requirement at the vehicle wheel and the total primary energy requirement for different energy carriers at constant fleets (© FVV)

FCEV = Fuel Cell Electric Vehicle, CI = Compression Ignition, SI = Spark Ignition, DI = Direct Injection, HPDI = High-pressure Direct Injection

FIGURE 3 Primary energy demand of road transport (passenger cars and commercial vehicles) for particular energy carriers and powertrain systems (© FVV)

469 TWh/a. By comparison, total electricity consumption in Germany was 515 TWh/a in the base year 2015.

For the calculation of the primary energy demand of road transport, **FIGURE 3**, however, the conversion losses in the production of the energy carrier used should not be neglected. As expected, the battery electric powertrain performs best with 249 to 325 TWh/a due to its low efficiency losses, even if a reconversion rate of 20 % is assumed. The upper value is less than 9 % of the total primary energy consumption in Germany in 2015 (3632 TWh/a). With centralized hydrogen production, the primary energy requirement for road transport increases to 502 to 574 TWh/a, which accounts for less than 16 % of the primary energy requirement in Germany. Due to the more complex production process, e-fuels show higher absolute values and a wider range from 774 to 1315 TWh/a. The best performing e-fuel is methane produced in a PtX process. In this case, road transport accounts for less than 24 % of the total primary energy demand.

Additional generation capacity for electricity, which is the starting point of

all energy paths, must be created in each scenario. If this capacity were created solely by additional offshore wind turbines in the German North Sea, **FIGURE 4**, 11,000 to 15,000 additional wind power plants with an average maximum output of 5 MW per turbine would have to be put into operation even in the battery electric scenario. Depending on the energy carrier and the efficiency of the subsequent power generation processes, the additional demand of a 100 % fuel cell fleet with centralized hydrogen production would increase the number to 23,000 to 26,000 additional plants. Approximately 43,000 to 49,000 additional plants would be required for the supply of FT gasoline/diesel. Since not only wind power but also solar energy would be used for the production of hydrogen and synthetic e-fuels, the energy demand of the MENA region was not translated into wind turbine numbers.

RESULTS: COSTS

If one only considers the distance-based energy costs for passenger cars, the battery electric powertrains achieve values between 1.99 and 4.68 euros/100 km

due to their higher degree of efficiency, not taking taxes and levies into account. Distance-based energy costs of fuel cell vehicles are 32 % higher in the best case for the centralized hydrogen production variants. Operation with e-methane increases energy costs by at least 116 %, while the values for other e-fuels are to some extent significantly higher. It should be noted that for reasons of comparability, the FVV experts did not include hybrid internal combustion engine vehicles into their calculations. In practice, however, hybrid powertrains achieve significantly lower fuel consumption.

The reverse is true for the infrastructure costs allocated to passenger car mileage. No additional costs are to be expected for liquid fuels produced on the basis of the FT process. The highest investment in e-fuels, from 0.06 up to 0.11 euros per 100 km, will be required in the transition to e-methane, as the filling station infrastructure will have to be expanded. The infrastructure costs for hydrogen distribution (centralized production) is between 0.39 and 0.79 euros per 100 km. The range for the battery electric scenario with 0.51 up to 2.87 euros/100 km is significant. Basically, this is due to the different assump-
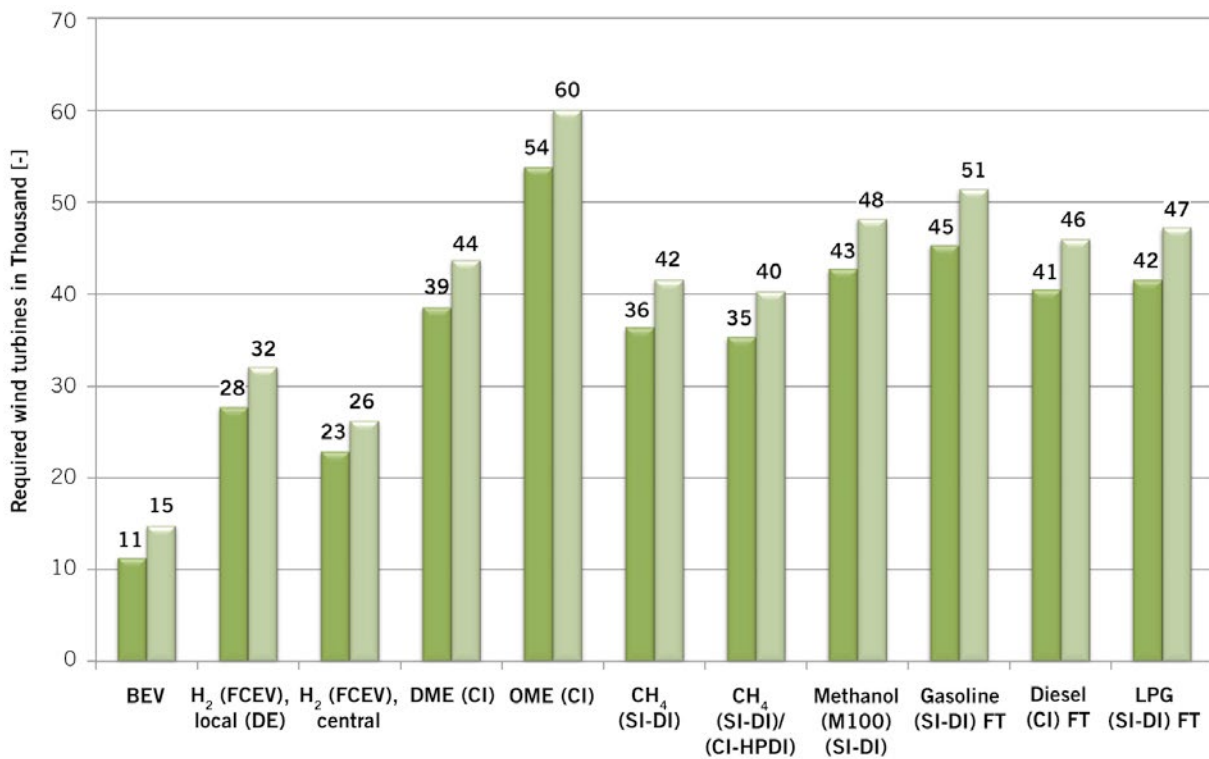
FIGURE 4 Required number of additional wind turbines (5 MW) to cover the primary energy demand of climate-neutral road transport (© FVV)
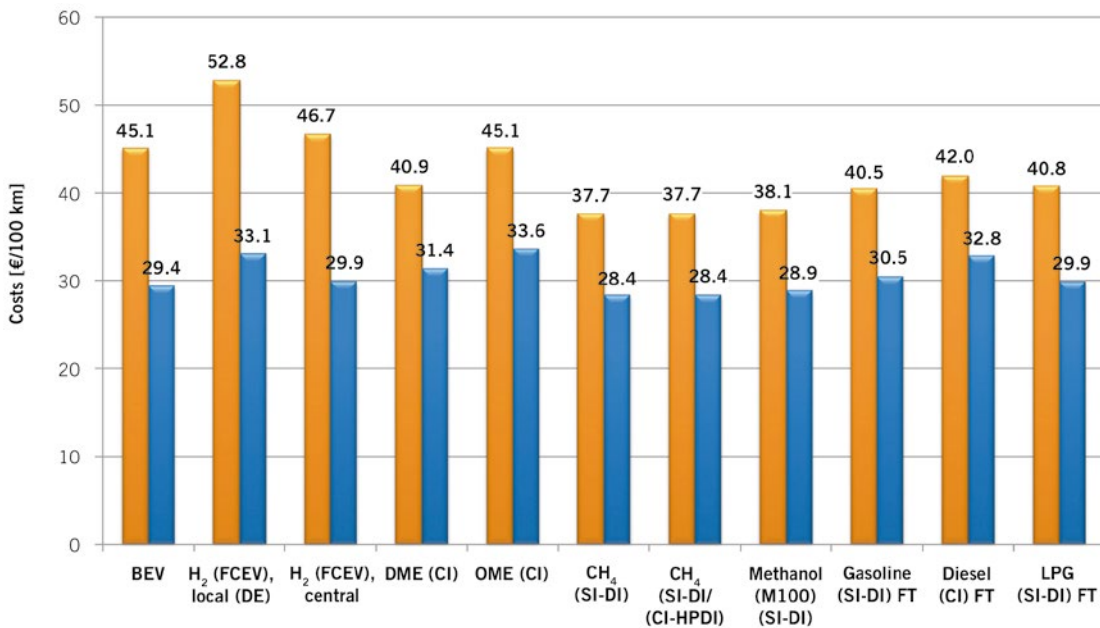
FIGURE 5 Minimum/ maximum mobility costs for passenger cars (© FVV)

FCEV = Fuel Cell Electric Vehicle, CI = Compression Ignition, SI = Spark Ignition, DI = Direct Injection, HPDI = High-pressure Direct Injection

tions regarding the required expansion of the power grid.

The scenarios for mobility costs, which include costs for the production of the energy carrier, infrastructure and the purchase of the vehicle, are converging considerably, **FIGURE 5**. This is due to the fact that the acquisition costs dominate the mobility costs. For passenger cars, minimum costs of 28.40 euros/100 km are achieved by e-methane fueled internal combus-

tion engine vehicles. Battery electric vehicles with 29.40 euros/100 km and fuel cell cars with 29.90 euros/100 km perform only slightly worse even in the best case. At 45.10 euros/100 km, the maximum costs of the most unfavorable electric fuel Polyoxymethylene dimethyl ethers (PODE or DMMn) are on par with the maximum costs for electricity used in battery electric vehicles. The maximum costs, which can also be described as a cost risk, are lowest when e-meth-

ane is used in passenger cars, closely followed by e-methanol.

For medium and heavy trucks, the dominance of vehicle acquisition costs is somewhat lower due to the high mileage. Nevertheless, here too the minimum costs are relatively close with exception of the scenario for hydrogen produced locally at the filling station, **FIGURE 6**. The lowest minimum costs are achieved, at 70.10 euros/100 km, by a dimethyl
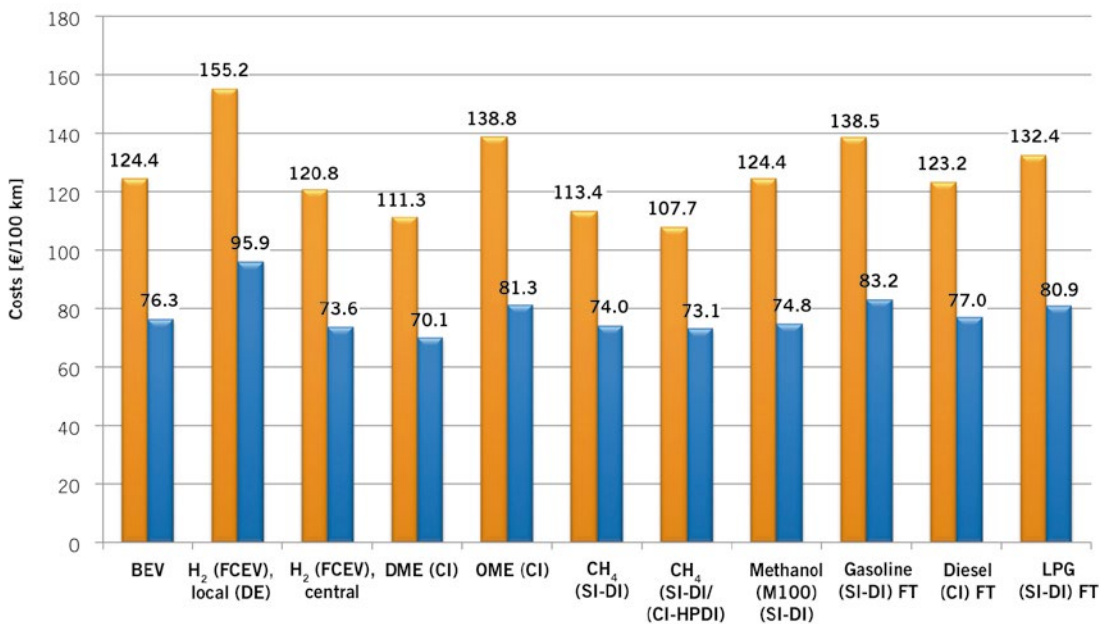

FIGURE 6 Minimum/ maximum mobility costs for commercial vehicles (© FVV)

–	1. Investment costs for power plants* [bn €]		2. Investment costs for fuel production [bn €]		3. Investment costs for infrastructure [bn €]		4. Cumul. add. vehicle costs** car (vs. gasoline) + truck (vs. diesel) [bn €]	
PtX	137-526	(Pt-CH$_4$)	102-118	(Pt-CH$_4$)	3-6	(Pt-CH$_4$)	0-122 + 24	(CH$_4$)
	166-629	(Pt-MeOH)	115-168	(Pt-MeOH)	< 1	(Pt-MeOH)	0-20 + 0	(MeOH)
	166-635	(Pt-FT)	176-254	(Pt-FT)	0	(Pt-FT)	82 + 0	(FT)
	149-570	(Pt-DME)	103-151	(Pt-DME)	1-2	(Pt-DME)	163-231 + 1	(DME)
	208-783	(Pt-OME)	167-243	(Pt-OME)	< 1	(Pt-OME)	163 + 0	(OME)
H$_2$	89-34	(central)	1771-87	(central)	19-38	(central)	163-850	(car)
	273-568	(local)*	55-66	(local)	19-128	(local)	37-125	(truck)
BEV	112-262*		0		38-198		163-768	(car)
							52-88	(truck)
–	**Energy supplier**		**Fuel industry**				**Automotive industry**	

* Including investment costs for Pt-CH$_4$ plants for reconversion and provision of a constant electrical power supply
** Cumulative additional vehicle costs (car vs. gasoline; truck vs. diesel) over 20 years: 3.4 million cars and 50,000 trucks per annum;
   assumption FT: (½ gasoline + ½ diesel)

ether(DME)-fueled internal combustion engine vehicle. Purely electric trucks drive at a minimum of 76.30 euros/100 km, fuel cell trucks at a minimum of 73.60 euros/100 km. E-DME achieves the lowest cost risk, followed by e-methane HPDI with 73.10 euros/100 km, while the cost risk for electric vehicles with 124.40 euros/100 km and fuel cell vehicles with 120.80 euros/100 km for centralized production is significantly higher.

Despite the high convergence of minimum costs, the scenarios differ in terms of investment needs. With a view to 100 % climate-neutral road transport, e-methane shows the lowest minimum investment requirement: up to 270 billion euros are needed according to the results of the study. A 100 % battery electric fleet leads to minimum investments of 360 billion euros, closely followed by the most favorable fuel cell scenario with 380 billion euros. The differences are considerably higher if the investment risk – considering the investment costs in the maximum scenario and sector in which they arise – is taken into account, **TABLE 2**. The highest investment risks arise for the hydrogen scenarios and the battery electric scenario. The automotive industry accounts for the largest share thereof.

RESULTS: MARKET ACCEPTANCE

Whether investments in a particular technology path actually lead to a reduction in greenhouse gas emissions is ultimately determined by market penetration, for which customer acceptance is the most important prerequisite. In addition to mobility costs, refueling time is an

important criterion for the customer. The particular energy carriers differ considerably in this respect. Even if we assume that battery electric cars are charged at a 150 kW fast charging station, the refueling time for a range of 100 km is still 500 s. In all other scenarios, this time interval is less than 30 s. For certain applications it will therefore definitely be indispensable to combine the battery electric powertrain with other propulsion systems.

In addition, admixture with conventional fuels can contribute to rapid market penetration. With today's infrastructure and taking into account the applicable fuel standards, admixture on a larger scale is only possible for four of the e-fuels investigated: e-methane and gasoline, diesel and LPG, which are obtained via the FT synthesis. The existing fuel standards allow the admixture of 2 vol% hydrogen to CNG sold today, e-methanol blending into gasoline is currently limited to 3 vol%. The study did not consider the compatibility of electricity with the existing vehicle stock. In reality, however, plug-in hybrid vehicles have already made it onto the road.

SUMMARY AND OUTLOOK

From a technically neutral standpoint, all three scenarios and various paths enable climate-neutral mobility. In this context, e-fuels will achieve a competitive position in terms of mobility costs. The calculation of the mobility costs shows that the vehicle costs, which are difficult to predict, dominate over the investments needed for the production and distribution of the energy carriers.

However, the cost risks for production and distribution also differ considerably depending on the scenario. This is clearly illustrated by the particular investment requirements for the necessary expansion of the electricity grid.

The underlying methodology of the 100 % scenarios – that is 100 % market share in 2050 – has proven to be suitable for the calculation of economically relevant costs. The very detailed calculation tool developed in the course of the study can be used for investigating mixed scenarios in the future.

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