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Climate-neutral driving in 2050:
Options for the complete defossilization of the transport sector.
Considerations based on results of the "FVV Fuels Study 2018".

Klimaneutrales Fahren in 2050:
Optionen zur vollständigen Defossilisierung des Transportsektors.
Betrachtungen auf Basis der „FVV-Kraftstoffstudie 2018".

Abstract

In accordance with the Climate Action Plan 2050, Germany is to become predominantly greenhouse gas-neutral by 2050. The complete defossilization of the transportation sector is not possible when vehicles are still operated with fossil fuels. In order to achieve a complete (100 %) carbon neutrality of the transport sector, a cross-industry working group under the coordination of the "FVV Fuels Group"- consisting of automotive, chemical, mineral oil and utility industry - has derived various pathways to defossilize the German transport sector.

In order to enable a simple and fair comparison between the different defossilization options, each scenario assumes the German vehicle population (passenger cars and trucks) to rely on one technology (100 % scenarios). Although all of these 100 % scenarios are only theoretical and therefore rather unrealistic, they are an appropriate tool for a technical and economical comparison.

The study focuses on a quantitative economic comparison of "mobility costs" (fuel production, expansion of distribution infrastructure, vehicle depreciation) and the primary energy demand of various fuel-powertrain combinations. Renewable energy is exclusively provided by solar and wind power for the following scenarios:

1. Direct use of electrical energy in battery electric vehicles (BEV).
2. Central and decentral hydrogen production for use in fuel cell electric vehicles (FCEV).
3. e-fuels (aka PtX fuels) with CO_2 from ambient air, for use in combustion engines.

For each scenario minimum and maximum assumptions have been applied, incorporating electricity costs for various production sites (Germany vs. Middle East and North Africa (MENA)), efficiency of electrolysis and PtX synthesis as well as cost variations for the invest in fueling infrastructure, necessary grid extension and vehicle depreciation. Beside the electrical pathway and two H_2-FCEV pathways, in total 8 different e-fuel options have been analyzed in detail, including two methane scenarios, methanol, DME, OME, and three Fischer-Tropsch fuels (e-gasoline, e-diesel and e-LPG).

As expected the energy demand is lowest for an all-electric scenario. Based on the 2015 German fuel consumption of 560 TWh, the primary energy demand for or a 100 % electric vehicle scenario can be reduced to 249 - 325 TWh per year. Depending on the scenario, the factor "Primary Energy FCEV (central H_2) / Primary Energy BEV" is in the range of 1.8 – 2.0, the factor "Primary Energy e-methane / Primary Energy BEV" in the range of 2.7 – 3.1, and the factor "Primary Energy e-FT-diesel/gasoline / Primary Energy BEV" approximately in the range of 3.3 – 3.8. These factors are calculated without any hybridization of the e-fueled powertrains and without any heating demand during cold periods.

Hybrid technology is already penetrating the vehicle market in considerable volumes and is expected to become a mainstream technology in the near future. Hybridization increases the vehicle efficiency, but also increases the vehicle costs. The fuel economy benefit as well as the on-costs are strongly dependent on the level of hybridization (mild or full hybrid), the vehicle basis and the operation conditions. In a parameter variation of this study an average hybrid system (average between mild and full hybrid) with an assumed 15 % efficiency benefit for an on-cost of € 1,460 per vehicle is applied to the passenger cars and delivery vans (up to 3.5 t gross vehicle weight) with internal combustion engine (ICE). Furthermore, the effect of cold-season operation is assessed. So far, the dataset of this study has been limited to

operation conditions with ambient temperatures above 20°C, without any cabin heating and battery heating demands.

Considering both, hybridization and cold-season operation, the FCEV pathway requires 1.6 – 1.8 times as much primary energy as the BEV pathway, the e-methane (HPDI) pathway 2.1 – 2.5 times and the e-FT-diesel/gasoline$_{(50/50)}$ pathway 2.6 – 3.0 times.

With respect to overall mobility costs (fuel costs + infrastructure costs + vehicle depreciation), all scenarios achieve comparable costs, as vehicle costs are dominating. Because future surcharges in particular for BEVs and FCEVs are very difficult to predict, there is a significant degree of uncertainty in the assessment of future mobility costs.

Including hybridization and cold-season operation, the FCEV pathway is at the same level of mobility costs as the BEV pathway (factor 1.01 -1.02). Mobility costs for e-methane can be up to about 20 % cheaper (factor 0.82 – 0.99) and e-FT-diesel/gasoline$_{(50/50)}$ can be slightly cheaper than the BEV pathway, but also a little more expensive (factor 0.88 – 1.09).

The lowest passenger car (LD) CO_2 abatement costs can be achieved with e-methane at 8 €/tCO_2 (without hybridization), which is 8.4 times lower than the minimum LD CO_2 abatement costs for BEV (67 €/tCO_2), even without consideration of a cold-season operation. A 50/50 e-FT-diesel/gasoline mix would require at least 197.5 €/tCO_2. The maximum abatement cost (the cost risk) for BEV amounts to 978 €/tCO_2, which is 1.8 times higher than the cost risk for e-methane (547 €/tCO_2) and 1.3 times higher than for a 50/50 e-FT-diesel/gasoline mix (755 €/tCO_2).

The minimum CO_2 abatement costs for heavy duty trucks (HD) can be achieved with e-DME at 95 €/tCO_2, which is 1.8 times lower than the minimum HD CO_2 abatement costs for BEV (168 €/tCO_2). A 50/50 e-FT-diesel/gasoline mix would require at least 213 €/tCO_2 (1.3 x BEV). The maximum abatement cost (cost risk) for "hybrid overhead pick-up battery electrical HD trucks" (HO- BEVs) amounts to 739 €/tCO_2, which is 1.4 times higher than for e-methane HPDI (541 €/tCO_2), but only 90% of the abatement cost risk for a 50/50 e-FT-diesel/gasoline mix (815.5 €/tCO_2).

The full defossilization of the transportation sector in Germany requires an enormous financial commitment. The decisive difference between the three main pathways (PtX, FCEV and BEV) is the sector in which the investments need to be taken. While for defossilization through hydrogen all involved partners (energy provider, fuel industry, infrastructure operators and the automotive industry/end customer) need to make significant investments, for all PtX pathways, the additional costs are almost exclusively incurred in electricity generation and fuel production. In the BEV scenario, main investment costs are in the energy production, infrastructure and grid extension as well as surcharges for the vehicles. The required investments in the infrastructure are highly dependent on assumptions and customer behavior.

Depending on the pathway, the total investment costs amounts to € 266 billion - € 1,740 billion. e-methane has the overall lowest minimum investment demand (€ 266 billion). A 100 % battery electric fleet requires at least € 364 billion investment. The differences are considerably higher when the "investment risks" (maximum cost scenarios) are considered. The highest investment risks arise for the hydrogen scenario (€ 1,442 billion) and the battery electric scenario (€ 1,317 billion). The lowest investment risks appear for e-methane (€ 796 billion) and e-methanol (€ 818 billion), followed by DME (€ 955 billion) and FT diesel/gasoline (€ 972 billion).

Motivation and Approach

The European Union overall greenhouse gas (GHG) emission target is an 80 % - 95 % reduction from the GHG emissions emitted in 1990, the German target of 95 % reduction is even tougher.

An FVV expert group has investigated different types of energy pathways, which theoretically all enable a GHG neutral, sustainable road mobility in Germany in 2050. Focus of the study is the technology neutral comparison of the primary energy demand and of the economic costs. Three different main pathways are compared (**Figure 1**):

1. Direct usage of renewable electricity in battery electric vehicles (BEV), complemented with an overhead pick-up (trolley line) on German motorways for long distance truck transport (aka HO-BEV)
2. Usage of hydrogen, produced by means of electrolysis operated with renewable electricity, in a fuel cell electric vehicle (FCEV).
3. Synthesis of e-fuels (aka PtX-fuels) from sustainably produced hydrogen and CO_2 from the ambient air. Afterwards usage in a combustion engine, spark ignited (SI) or compression ignited (CI), depending on the fuel.

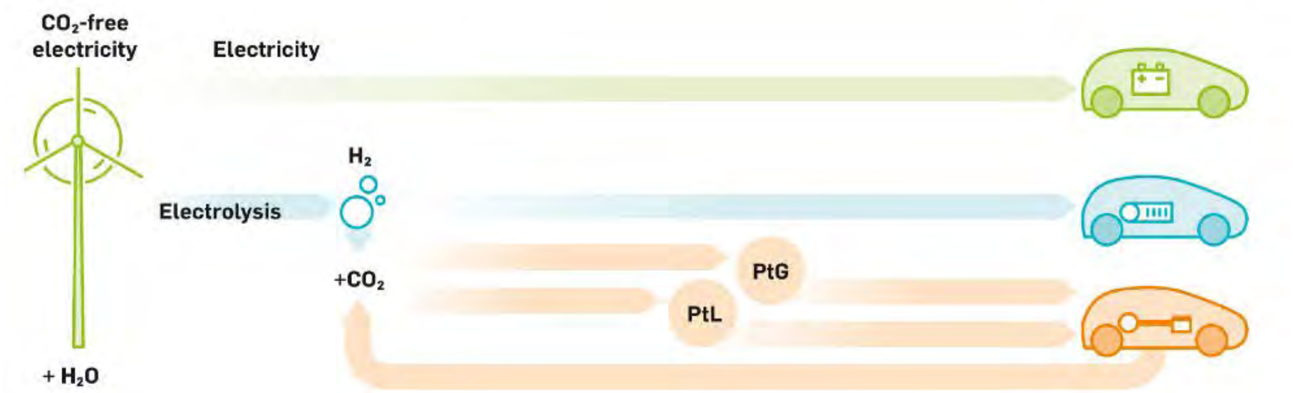

Figure 1: Energy pathways for completely defossilized road transportation (100 % scenarios)

In order to compare the economic impact the different energy pathways, they have been considered as “100 % scenarios”, meaning that 100 % of the vehicle population is replaced by one single technology. Although these 100 % scenarios are theoretical and relatively unrealistic, they are very useful tools for analyzing technology potential and comparing technical and economic suitability. The described conclusions do not merely reflect the opinion of a single industry partner involved in the study, but are rather to be viewed as the cross-industry synthesis of this joint study. A more realistic superposition of different technologies (e.g. fleet mix, hybridization) based on the derived data can be the content of a follow-up study.
Bio-fuels are not regarded in this study as their potential is considered to be by far not sufficient for a 100 % scenario (limitation of arable land), while sustainable electricity, sustainably hydrogen and e-fuels have the potential to replace fossil fuels completely. Nevertheless, bio-fuels can be a significant supplement for the considered PtX scenarios.
The point of origin for each investigated scenario is a complete changeover of the power generation to renewable energy (wind and solar power). In general, there is enough solar and wind potential for a complete defossilization of the transport sector, regardless of which PtX fuel considered.” [1].

Boundary Conditions and Assumptions

Two sub-scenarios are investigated for the “hydrogen – FCEV” scenario and eight for the “e-fuel scenario”. The specific boundaries for those scenarios are shown together with the BEV scenario in **Table 1**.

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 periods	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 periods	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) Minimum cost scenario: production in MENA* (2030) Maximum cost scenario: production in Germany (2017)	No additional energy storage. Energy storage for dark periods in the fuel itself (surplus production when solar/wind power is available)	Local liquefaction (for CH_4 and H_2) Transport of liquid fuel by ship (from MENA) + 500 km truck transport in Germany (for fuel from MENA and Germany)
E-methane (vehicle: pressure tank)	SI engine (λ=1)			
E-methane (car: pressure tank, truck > 3.5t: liquefied methane (LNG))	SI engine (λ=1) HPDI CI engine (> 3.5t)			
E-methanol (M100)	SI engine (λ=1)			
E-gasoline (Fischer-Tropsch)	SI engine (λ=1)			
E-propane (LPG) (Fischer-Tropsch)	SI engine (λ=1)			
E-diesel (Fischer-Tropsch)	CI engine			
E-OME	CI engine			
E-DME	CI engine			

*MENA = Middle East North Africa

Table 1: Framework conditions of the investigated pathways (100 % scenarios)

Permanent Electrical Energy Supply vs. Intermittent Electrical Energy Generation

A prerequisite for each pathway is that re-filling with energy of each vehicle is possible at any time in order to fulfill customer requirements of timely unrestricted vehicle usage. This is an important requirement in an entirely sustainable world, where electrical power is primarily generated by highly volatile sources as wind and solar power. Dark periods – when neither the sun is shining, nor the wind is blowing – can easily last up to two weeks in Germany. In those periods, BEVs need to be operable and thus require recharging. In order to also supply electrical power in those periods an energy buffer is required in the power generation infrastructure. Fossil coal or fossil gas power plants are no longer available in a 100 % sustainable energy supply. In accordance to [2], a 20 % energy buffer is assumed to stabilize the electrical power supply. Even if batteries are used for short term buffering and hydropower potential (pumped storage power plants) is respected, long term buffering of large quantities over 2 weeks or seasonal storage is only possible with Power-to-X technologies in the background.

Therefore, a Pt-methane (e-methane) production with 60 % efficiency is assumed as buffer input during positive energy supply periods. A gas (methane) power plant with also 60 % efficiency is assumed to deliver electrical power during dark periods. Losses of the storage process itself are neglected.

This buffering is not necessary for central e-fuel (and hydrogen) production, because the e-fuel or hydrogen itself serves as a buffer.

BEV mobility requires primarily a domestic energy production, since the energy is distributed by the power grid and the grid is not connected with very profit-yielding windy and sunny areas as e.g. Middle East North Africa (MENA). It is also very unlikely that such a grid extension will be available in a foreseeable future. On the contrary, e-fuels and e-hydrogen can be produced in profit-yielding areas and then be shipped to Germany. Those boundary conditions are important when in particular the minimum cost scenarios are compared.

A maximum cost scenario and a minimum cost scenario are developed for each pathway in order to set limits for future mobility costs. While the maximum cost scenario unifies the worst case cost and efficiency assumptions, the minimum cost scenario contains the best case cost and efficiency assumptions. Details are documented in [3].

In the minimum cost scenario, e-fuel and the central hydrogen production are considered to be located in MENA. For transportation of all e-fuels from MENA to Germany, shipping in liquid form is assumed (also for the gaseous fuels). Hydrogen and methane are cooled for liquefaction (as L-H_2 and LNG). Renewable energy for BEV and the local on-site H_2-production (at the filling station) is based on domestic renewable energy sources.

This study covers eight different powertrain-fuel scenarios that are currently under discussion. Three of these e-fuels are vehicle fleet compatible Fischer-Tropsch e-fuels, such as e-gasoline, e-diesel and e-LPG. The Fischer-Tropsch process delivers a sustainable crude as input for the refinery, similar to the stream today. Hence, Fischer-Tropsch fuels can only be evaluated together, not as single streams, even if they are handled as single streams within the calculations of this study.

Approximation of Technology Specific Future Energy Demand

The basis for calculation of the primary energy demand for each pathway is the real fuel consumption in Germany 2015 (560 TWh; thereof 440 TWh for passenger cars and 120 TWh for trucks). By means of an approximated fleet efficiency (passenger car 23 %, heavy duty 35 %) a mechanical energy demand (energy demand "on the wheel", 143 TWh, **Figure 2**) is calculated. Afterwards the "future energy demand" is calculated by today's available "best-in-class" efficiency of each pathway. In order to focus on neat pathways, hybridization has not been considered. For all scenarios, the same base vehicle is used and side effects, as e.g. increasing transportation demand, are eliminated to maintain simple comparability.

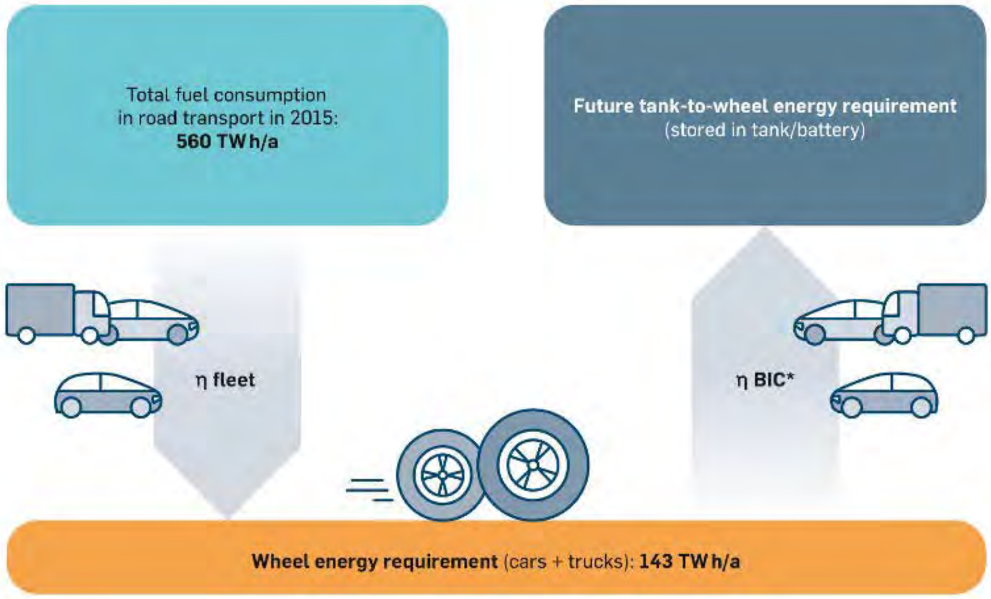

Figure 2: Approxmation of real world energy demand for each scanrio

Mobility Cost Definition

Mobility costs include the fuel production and distribution infrastructure costs (all calculated with the same "return of invest" of 6 % and interest rate of 4 %) as well as the vehicle depreciation. They are separately calculated for passenger cars and trucks and are expressed in €/km, which is the same unit as usually used for total cost of ownership (TCO) comparisons. However, different from the TCO, fuel taxes, vehicle insurance costs and service costs are not included in the mobility costs of this study.

For competitive reasons, the cost of purchasing a passenger car is set at a flat rate of € 20,000 for a model from the compact vehicle segment powered by a spark ignited (SI) engine. Based on current vehicle price lists, the extra charge for a comparable compression ignited (CI) engine-driven vehicle is € 2,400 (for both scenarios, minimum and maximum cost).

For the maximum cost scenario, on-cost values from several sources are considered for each technology. The on-cost for the passenger car scenarios are based on OEM vehicle price lists (diesel, methanol - in accordance to E85 vehicles) or are derived from the Roland Berger Auto Oil Study 2015 [5], which predicts vehicle on-costs for 2030 (methane, BEV, FCEV) or are approximated by retro-fit price lists (DME, LPG). The additional costs of up to € 11,300 for a battery electric car with a nominal range of 500 km and € 12,500 for a fuel cell vehicle are based on forecasts for 2030 according to [5].

For the minimum cost scenario a very simple approach is chosen, assuming cost parity between diesel vehicles and a BEV500 (battery electric vehicle with 500 km range) as well as an FCEV. Technical evidence for the cost parity could not be discussed due to compliance rules.

For passenger cars vehicle depreciation is calculated in accordance to ADAC data on the basis of an exemplary C-segment vehicle with a gasoline engine and a sales price of € 20,000, which is significantly (approx. € 10,000) below the average German sales price in 2017 [6]. The assumed depreciation is based on 4 years and an annual driving range of

15,000 km. Heavy-duty depreciation is calculated based on an exemplary long-distance trailer truck for € 90,400 sales price. The purchase costs for trucks are calculated from the average of the prices of various CI engine driven commercial vehicles available today. The extra charge for full electrification is estimated at € 52,000 to 87,500. Additional costs of € 36,500 to €125,000 are assumed for a fuel cell powertrain system. A conversion to e-methane may cost between € 14,000 € (SI, Lambda 1) and € 24,000 (HPDI), depending on the combustion process.

As furtherly shown in **Table 2** electrolysis efficiency, BEV charging efficiency, CO_2 absorption cost, electrical energy cost, as well as infrastructure assumptions are also distinguished between the minimum and the maximum cost scenario.

Electricity Costs

Fuel production costs are mainly determined by the electricity costs. For intermittent renewable power supply for PtX processes, the maximum cost scenario is based on today's (2017) power supply costs from offshore wind turbines in the North Sea of 88.10 €/MWh, while the minimum cost scenario assumes production in the MENA region (Middle East and North Africa) in 2030 at 24.26 €/MWh (mix of wind and solar power). However, the costs of permanent power supply required by the "battery electric" and "locally produced (decentralized) hydrogen“ pathways are expected to range between 100 and 180 €/MWh. These costs consider both, the PtG storage process and the gas-fired power plants required to bridge power failure in dark periods. A depreciation period of 20 years is assumed for the installations required in the subsequent process steps (electrolysis, PtX synthesis including CO_2 separation and liquefaction).

Infrastructure Assumptions

Investments in the energy distribution infrastructure are largely dependent on the number and unit costs of charging points or filling stations. The minimum cost scenario considers a supply of 5,000 fully capable car filling stations (8 pumps per station with a back-to-back re-fill capability of at least 6 vehicles per hour, equivalent to 40,000 filling points), and 6,000 additional filling points for trucks to be sufficient for all e-fuels and hydrogen. The number of 5,000 is assumed because of the fact that customers seem to be satisfied with the number 6,800 available LPG stations in Germany, but not with the 900 CNG stations. In the maximum cost scenario, 10,000 fully equipped filling stations are assumed, which seems to be a sensible consolidated number of the approx. 14,000 stations available in Germany today.
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 pick-up lines required to electrify long-distance freight transport („electric highways“). The minimum scenario, according to [4], is based on the assumption that 4,000 kilometers of federal motorways need to be equipped with overhead pick-ups, while in the maximum scenario the entire German motorway 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, i.e. the minimum cost scenario, the experts assume that no network expansion is necessary (e.g. charging times follow the energy supply, no fast charging, no balancing of peak loads as e.g. at the start of holidays). In the maximum cost scenario, additional € 98 billion need to be invested into the expansion of

the electricity grid, thereof € 77 billion into the grid extension for light duty vehicles and € 21 billion into the installation of overhead pick-up lines on motorways for heavy-duty trucks. Light duty vehicle charging is assumed to use 5,000 full load hours of grid capacity utilization per year. Fast charging is included. The depreciation period is 40 years. .

Scenario	Min. costs (max. efficiency)	Max. costs (min. efficiency)
Electrolysis energy requirement PtX production (incl. H_2)	Alkaline electrolysis 45.61 kWh / kg H_2 (degree of efficiency: 0.73)	Alkaline electrolysis 53.40 kWh / kg H_2 (degree of efficiency: 0.62)
CO_2 source for PtX production	From ambient air (€ 124.50 / t CO_2)	From ambient air (€ 292.80 / t CO_2)
Electricity price BEV and FCEV / H_2 local	Permanently available Germany 2030: € 100/MWh	Permanently available Germany 2015: € 180/MWh
Electricity price FCEV / H_2 central and all other PtX processes	Alternating, MENA PV + wind 2030: € 24.26 / MWh (€ 15 / MWh PV, € 25 / MWh wind)	Alternating offshore wind, Germany 2015: € 88.10/MWh
Amortization of investment in fuel production	20 years, ROI 6 %, interest 4 %, maintenance 5 %, residual value 0	20 years, ROI 6 %, interest 4 %, maintenance 5 %, residual value 0
Degree of efficiency for transmission/charging for BEVs	Maximum: 0.94	Minimum: 0.72
Infrastructure	Filling stations: - Car: 40,000 filling points - Truck: 6,000 filling points Car - BEV charging stations: - 80,000 quick-charge stations - 12.5 million home charging stations - 5 million workplace charging stations Hybrid-overhead line truck: Overhead line 4,000 km Assumption: NO electricity grid expansion required for BEV / connection of local H_2 electrolysis	Filling stations: - Car: 80,000 filling points - Truck: 12,000 filling points Car - BEV charging stations: - 160,000 quick-charge stations - 25 million home charging stations - 10 million workplace charging stations Hybrid-overhead line truck: Overhead line 13,000 km Electricity grid expansion for BEV charging stations: € 77.4 billion, costs for connecting overhead lines for trucks: € 21 billion, connection of local H_2 electrolysis: € 90 billion
Amortization of investment in infrastructure	40 years, ROI 6 %, interest 4 %, maintenance 5 %, residual value 0	40 years, ROI 6 %, interest 4 %, maintenance 5 %, residual value 0
Vehicle costs for cars	No surcharge for all SI concepts (based on gasoline vehicle for € 20,000) + € 2,400 for all CI concepts compared to SI (taken from current manufacturers' price lists) Assumption (QED) for BEVs and FCEV: Same price as for diesel vehicle will be possible in 2050	[Berger 2016]: (forecasts for 2030) + current manufacturers' price lists (based on gasoline vehicle for € 20,000): BEV 500 + € 11,300, FCEV + € 12,500, DME + € 3,400, diesel/OME + € 2,400, methane + € 1,800, propane + € 1,500, methanol + € 300
Vehicle costs for trucks	From [LastOm 2017], p. 293 ff. (DEKRA), (basis: trailer truck € 90,400): Red. price FCEV and BEV from "Update DOE - Fuel Cell Technologies Office, chapter 3.3 + 3.4" hybrid-overhead line EV + € 51,978, FCEV + € 36,538, DME/propane + € 1,000, diesel/OME/gasoline + 0, methane + € 14,000 or € 24,000 (HPDI)	From [LastOm 2017], p. 293 ff. (DEKRA), (basis: trailer truck € 90,400): hybrid-overhead line + € 87,500, FCEV + € 124,740, DME/propane + € 1,000, diesel/OME/gasoline + 0, methane + € 14,000 or € 24,000 (HPDI)

Table 2: Minimum and maximum cost scenario: assumptions [3]

Results

Energy Demand

The annual tank-to-wheel (TtW) energy demand is shown in **Figure 3.** The high efficiency of a battery electric vehicle leads to an annual tank-to-wheel (TtW) energy requirement of 176 TWh, which is 31% of the actual road transport energy demand in 2015 (560 TWh). A 100 percent FCEV fleet, however, has a higher tank-to-wheel energy requirement of 307 TWh/a (55 % of road transport energy demand 2015). For e-fueled vehicles, the future TtW energy demand ranges from 431 to 469 TWh/a (approx. 80 % of road transport energy demand 2015). In comparison, total electricity consumption in Germany was 515 TWh/a in the year 2015.

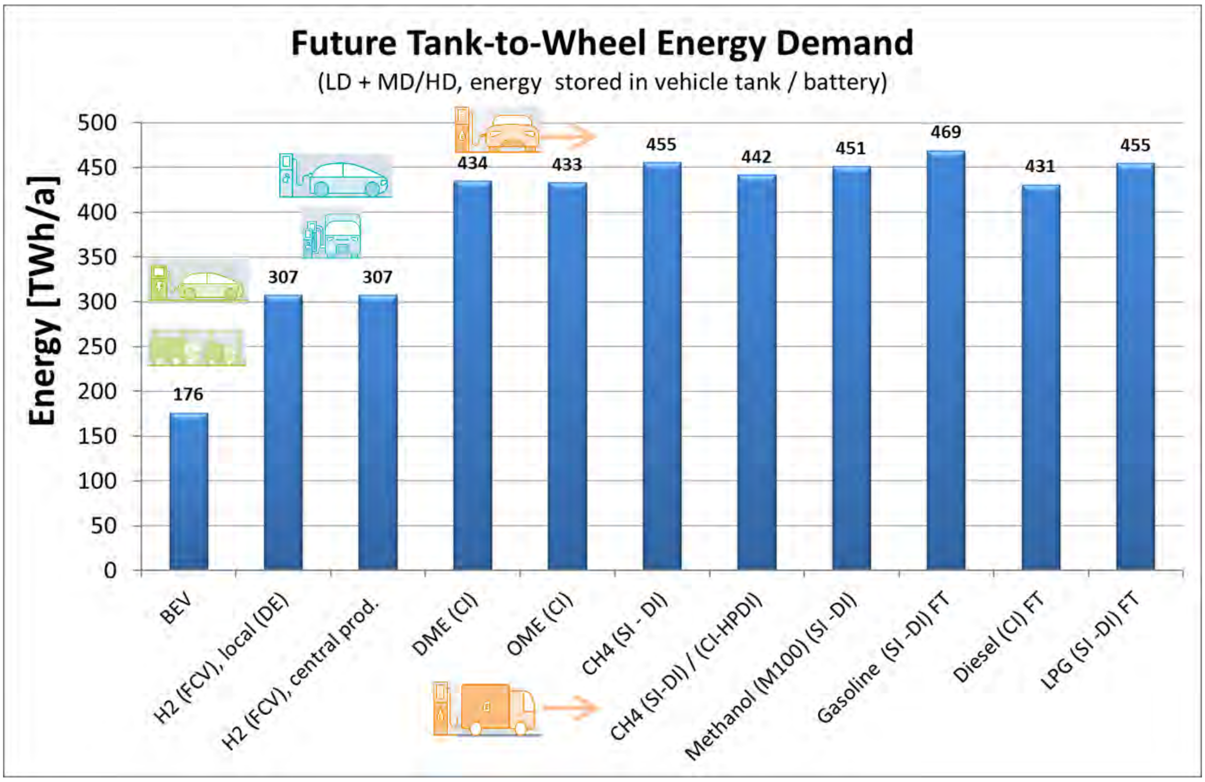

Figure 3: Annual tank-to-wheel energy demand

Figure 4 displays the primary energy demand, which contains also the energy buffer losses required for the BEV and local FCEV scenario. For the calculation of the primary energy demand, the conversion losses in the production of the energy carrier to buffer dark periods (methane production with 60 % efficiency) and re-powering the e-methane by means of a gas power plant (60 % efficiency) are included (the storage efficiency losses itself are assumed to be negligible). As expected, the battery electric powertrain performs best with 249 to 325 TWh/a due to its low efficiency losses. The upper value is less than 9 % of the total primary energy consumption in Germany in 2015 (3,632 TWh/a). With centralized hydrogen production, the primary energy requirement for road transport increases to 502 to 574 TWh/a, which accounts for 14-16 % of the primary energy requirement in Germany 2015. Due to the more complex production process, e-fuels show higher absolute values and a wider range from 774 to 1,315 TWh/a. The best performing e-fuel is methane, which results in a demand of 21-24 % of the total primary energy demand in 2015. Fischer-Tropsch production requires approx. 26 – 29 %.

Depending on the scenario, the factor “Primary Energy FCEV (central H_2) / Primary Energy BEV” is in the range of 1.8 – 2.0; the factor “Primary Energy e-methane / Primary Energy BEV” in the range of 2.7 – 3.1, and the factor “Primary Energy e-FT-diesel/gasoline / Primary Energy BEV” approximately in the range of 3.3 – 3.8. It is important to note, that these factors are calculated without any hybridization of the e-fueled powertrains and without any heating demand for electric vehicles during cold periods. Those considerations will lead to decreased factors and are content of the parameter variation in a further chapter of this paper.

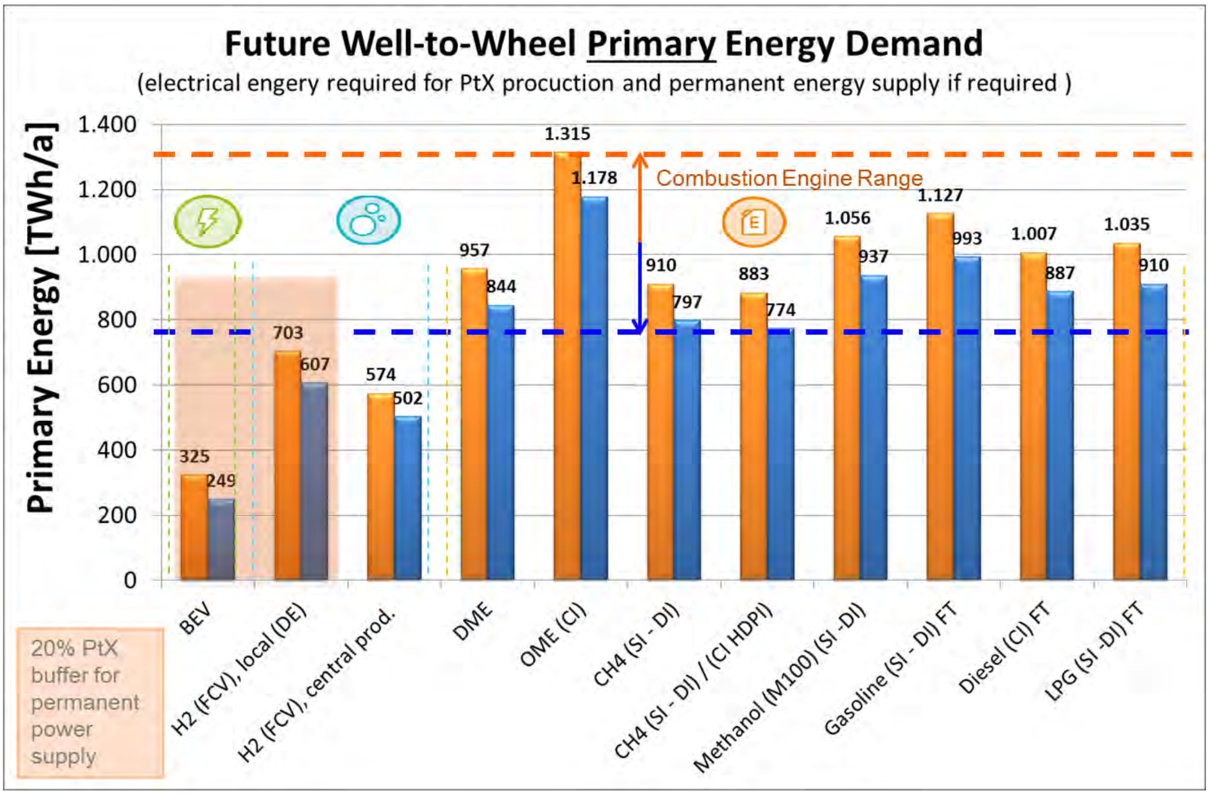

Figure 4: Annual primary energy demand

For electricity, which is the starting point of all energy pathways, additional generation capacity must be created in each scenario. If this capacity is created solely by additional offshore wind turbines in the German North Sea, 11,000 – 15,000 additional turbines with an average maximum output of 5 MW per turbine would have to be put into operation even in the battery electric scenario (**Figure 5**). Depending on the energy carrier and the efficiency of the processes, the e-fuel pathways (inclusive H_2) require a higher number of wind turbines. The additional demand of a 100 % FCEV fleet would increase the number to 23,000 - 26,000 offshore wind turbines (minimum requirement for centralized production in Germany). Between 35,000 and 40,000 wind turbines are required to support the HDPI e-methane scenario, while approximately 43,000 – 49,000 additional wind turbines are required for the supply of Fischer-Tropsch (FT) gasoline and diesel (50/50 e-gasoline/e-diesel share assumed). Since not only wind power but also solar energy would be used for the production of hydrogen and synthetic e-fuels in Middle East and North Africa (MENA), the energy demand of the MENA region is not recalculated into wind turbine numbers.

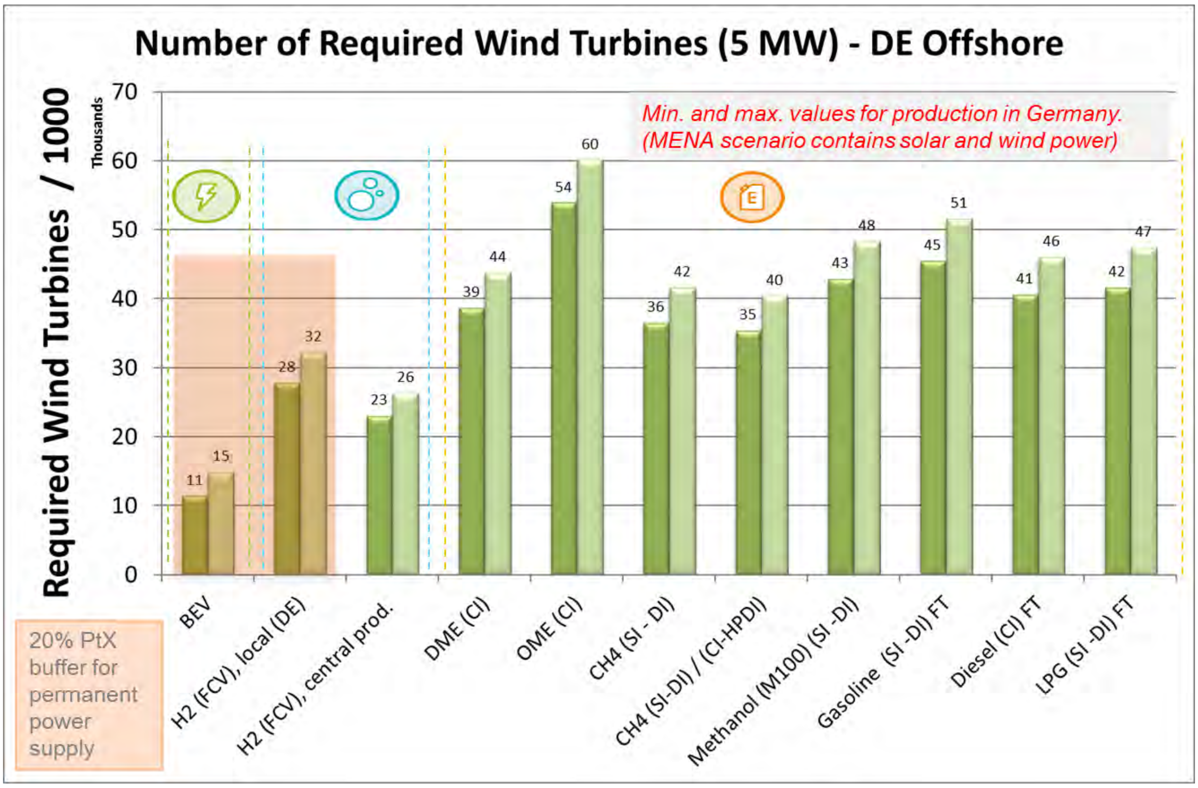

Figure 5: Required number of additional offshore wind turbines (5 MW North Sea)

Energy Costs

Figure 6 displays the energy, respectively fuel costs per energy unit. The prices per kWh displayed for the BEV scenario are higher than the assumed electricity prices for buffered wind energy, as transmission losses and losses related to quick charging are included. In the minimum cost scenario, the energy costs for the BEV scenario are € 0.11 per kWh.

In the minimum cost scenario, e- fuels produced in MENA are cheaper in relation to the energy content than energy for electro mobility: -27 % for hydrogen generated centralized in MENA (€ 0.08 per kWh) and -18 %, for methane produced centralized in MENA (€ 0.09 per kWh). Locally generated hydrogen (€ 0.18 per kWh in the best case) has the lowest potential with regard to the energy related costs (+82 % compared to BEV).

In case e-fuels are produced centrally in Germany under the least favorable conditions (maximum cost scenario), the central production of H_2 appears to be the variant with the lowest costs at € 0.22 per kWh, followed by CH_4 (€ 0.23 per kWh) and BEVs (€ 0.25 per kWh, permanent electrical power supply). FT fuels can cost up to € 0.32 per kWh and OME up to € 0.37 per kWh.

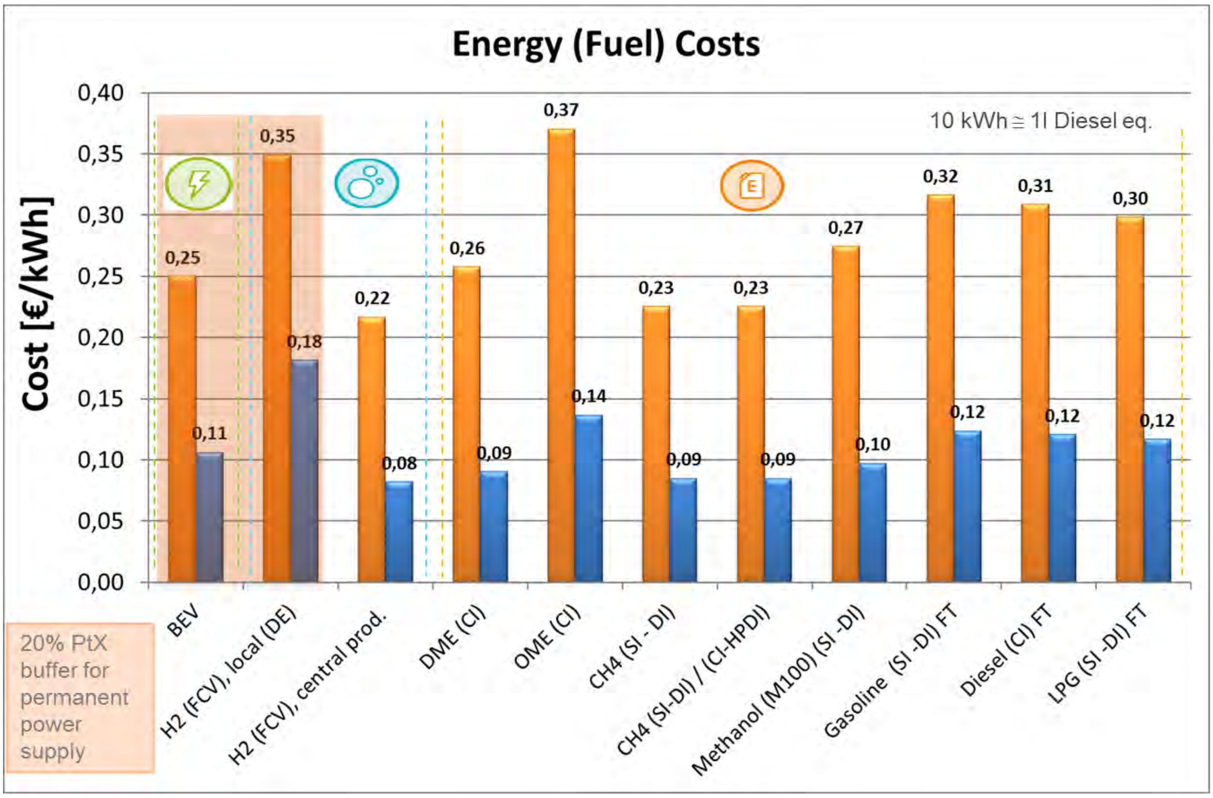

Figure 6: Energy related fuel costs (min. /max.)

Figure 7 displays the energy (fuel) costs per km without consideration of taxes and levies. Due to the higher efficiency in BEVs, the purely electric variants are the cheapest solution with regard to distance-related fuel costs. Battery electric powertrains achieve values between 1.99 and 4.68 €/100 km. 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 basic calculations. In practice, however, hybrid powertrains will achieve significantly lower fuel consumption and are discussed in the chapter “Parameter Variation” of this paper.

In order to build up a new distribution infrastructure, no additional costs are expected for liquid fuels produced by the Fischer-Tropsch process. The highest investment in e-fuels (0.06 - 0.11 €/100 km) will require the conversion to e-methane, as the filling station infrastructure will have to be expanded. The infrastructure costs for hydrogen distribution and fueling infrastructure (centralized production) is between 0.39 and 0.79 €/100 km, while the range for the battery electric scenario with 0.51 - 2.87 €/100 km is significant. Main reason for the large difference between the minimum and the maximum in the BEV scenario are the different assumptions with regard to the required expansion of the power grid.

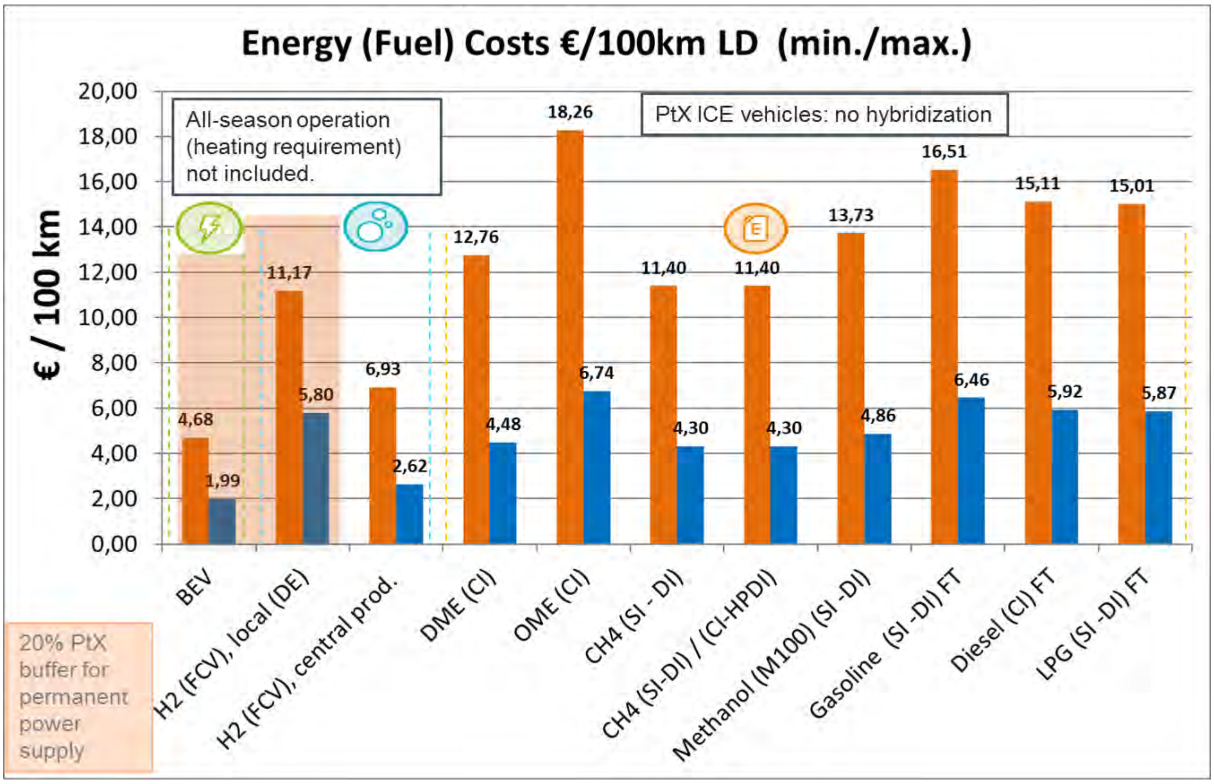

Figure 7: Fuel costs per km (min. /max.)

Mobility Costs

Though energy cost and infrastructure cost vary widely within the studied fuel pathways, the mobility costs of the different scenarios, which include the costs for the production of the energy carrier, costs for the necessary infrastructure as well as costs for the purchase of the vehicle, are converging considerably as shown in **Figure 8**. This is due to the fact, that the vehicle depreciation dominates the mobility costs, which is displayed for the minimum cost scenario in the mobility cost break down in **Figure 9**.

For passenger cars, 28.4 €/100 km are achieved by e-methane fueled internal combustion engine vehicles in the minimum cost scenario. Battery electric vehicles with 29.4 €/100 km and fuel cell passenger cars with 29.9 €/100 km are only slightly more expensive in the optimistic scenario. In the max cost scenario the costs of the most unfavorable e-fuel (OME) with 45.1 €/100km are on a par with the maximum costs of battery electric vehicles. The maximum costs, which can also be described as a "cost risk", are lowest when e-methane is used in passenger cars, closely followed by e-methanol.

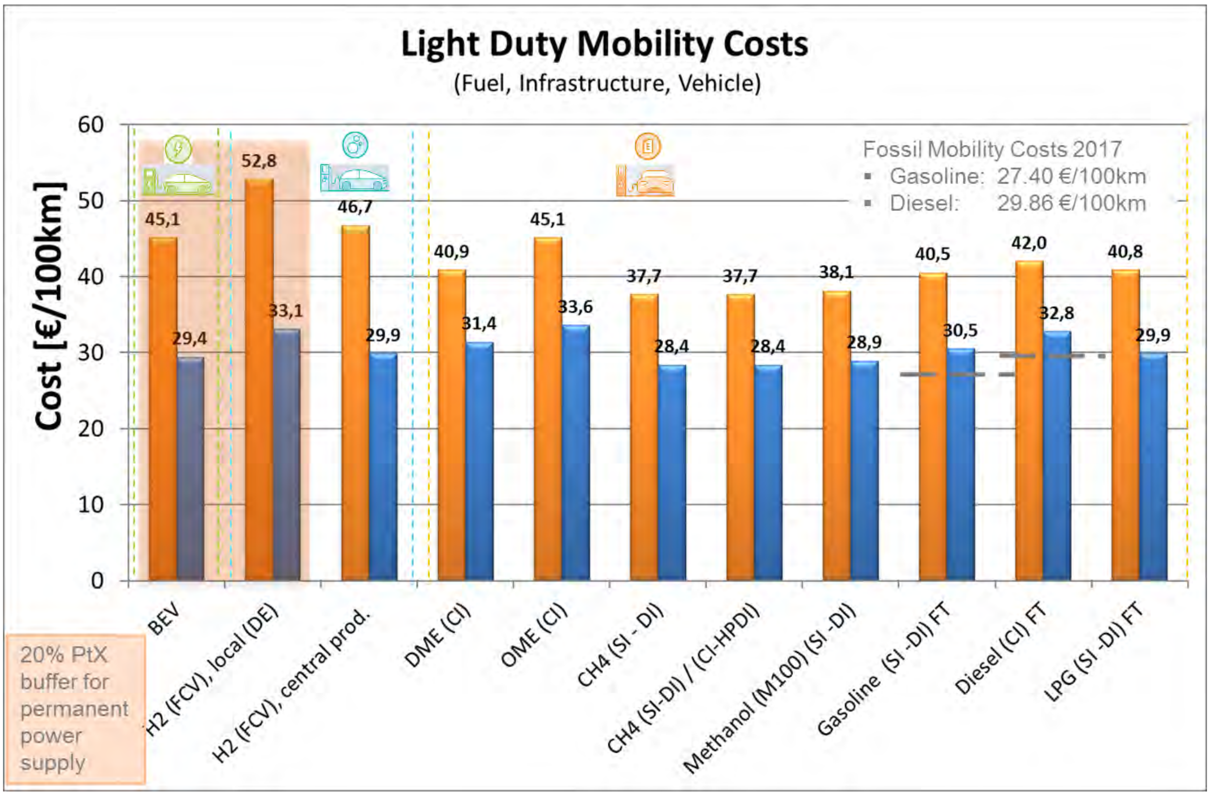

Figure 8: Mobility costs for passenger cars (min. /max.)

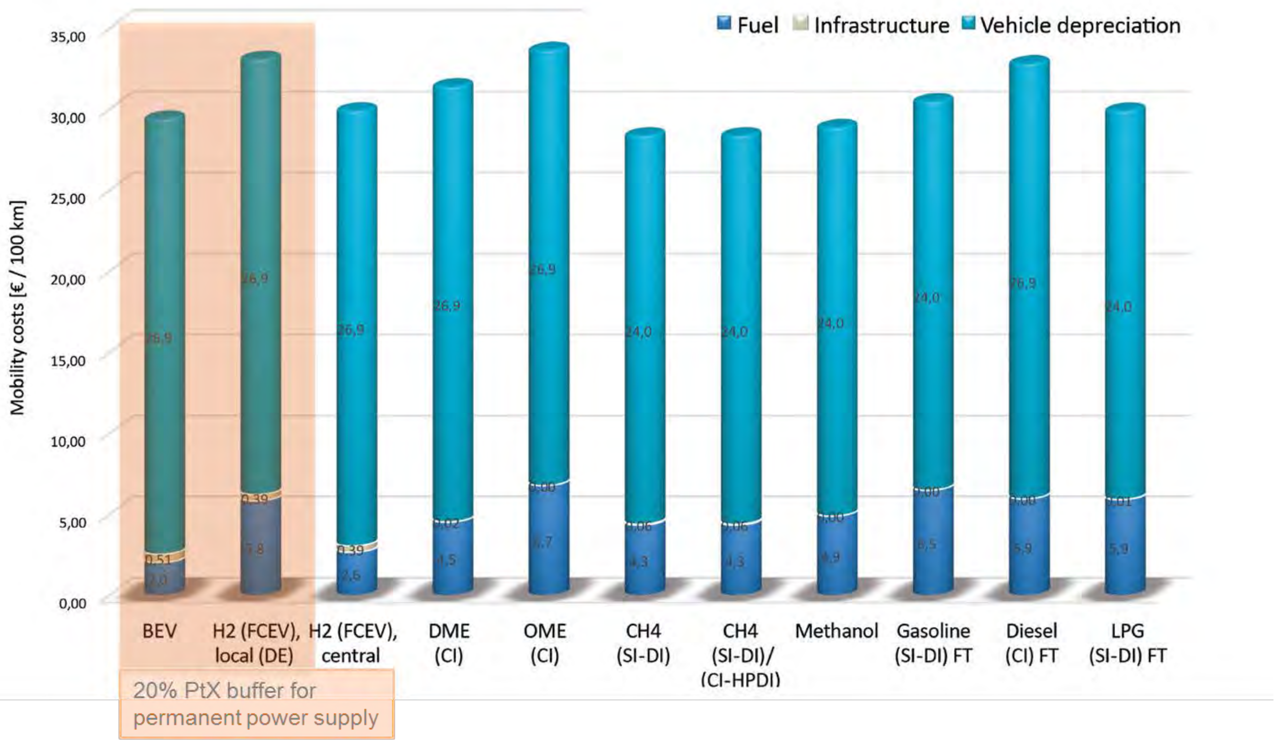

Figure 9: Cost break down for minimum mobility costs of passenger cars

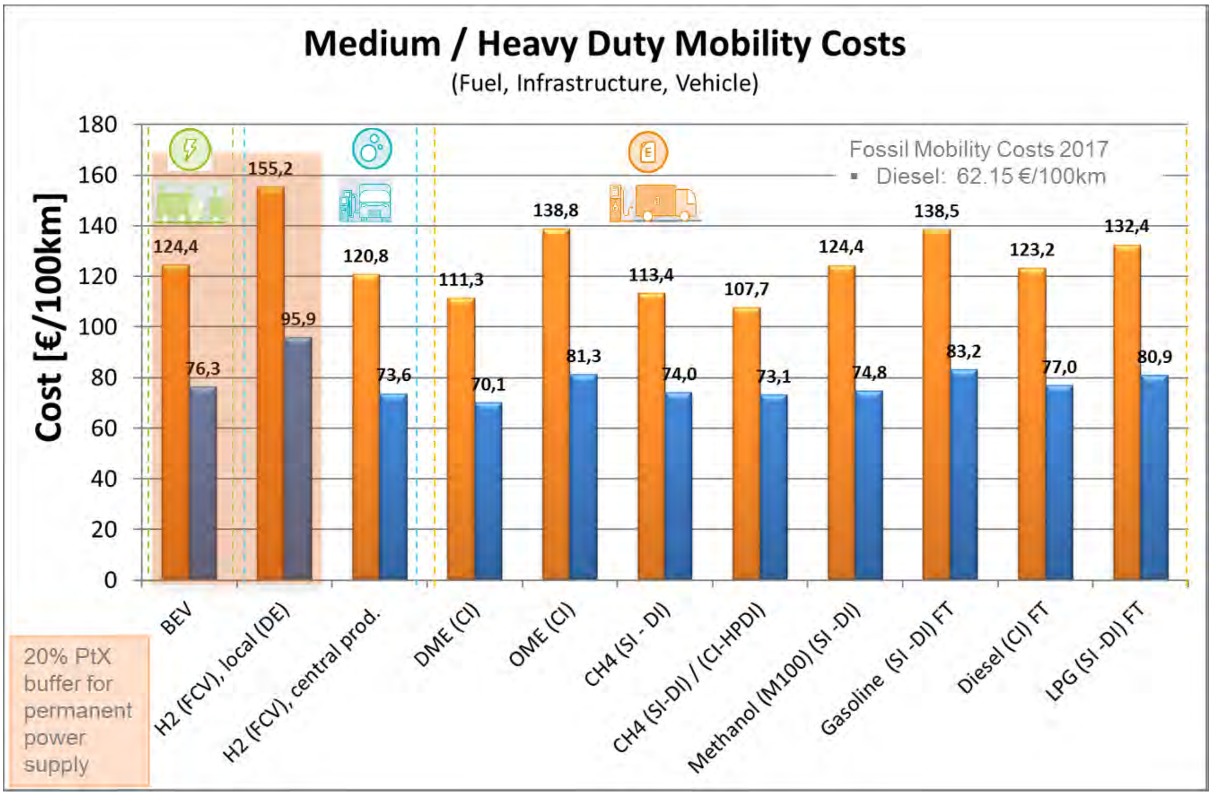

Figure 10: Mobility costs for heavy-duty trucks (min. /max.)

For medium and heavy trucks (**Figure 10**), the dominance of vehicle depreciation is somewhat lower due to the high mileage. Nevertheless, here also the minimum costs are in the same ballpark, with the exception of the locally (at the filling station) produced hydrogen scenario. The lowest minimum costs (70.1 €/100 km) are achieved by a DME-fueled compression ignition (CI) powertrain, directly followed by methane HPDI (73.1 €/100 km) and by centrally produced hydrogen used in a fuel cell powertrain (73.6 €/100 km). Purely electric truck operation is more expensive with minimum mobility costs of 76.3 €/100 km. E-DME achieves the lowest “cost risk” (111.3 €/100 km), followed by e-methane (HPDI: 107.7 €/100 km; stoichiometric SI: 113.4 €/100 km), while the “cost risk” for electric vehicles (124.4 €/100 km) and fuel cell vehicles (central production 120.8 €/100 km) is higher.

CO_2 Abatement Costs

As all of the sustainable transportation pathways require more expenses than - fossil fuel driven - road transportation today, CO_2 abatement costs are of interest. Those costs describe the costs per ton of CO_2 avoided by the introduction of a new technology. In this paper, CO_2 emissions are calculated on a “well-to-wheel” approach for the use phase of the car, neglecting emissions from car production and disposal. The abatement costs are calculated as the difference of the mobility costs with the 100% sustainable fleet versus the mobility costs of an average gasoline / diesel fleet today. The mobility costs are consisting of fuel costs, infrastructure costs and vehicle depreciation, expressed in €/100km, as calculated for all investigated sustainable pathways in this paper.

The reference fossil fuel costs are calculated based on the average “product price” of gasoline and diesel fuel in Germany 2018 (average: January - November 2018) – in accordance to MWV Germany [7]. The “product price” excludes taxes and profit margins and amounts to

0.5684 €/l$_{Gasoline}$ and 0.6085 €/l$_{Diesel}$. Furthermore, the fuel consumption figures of the diesel and gasoline reference vehicle already used in the FVV fuels matrix are applied to the reference fossil fuel cost calculation. The basis of those fuel consumption figures is the total fuel consumption in Germany 2015 (560 TWh) (fuel consumption per passenger car: gasoline 187.7 MJ/100km, diesel 176.2 MJ/100km; heavy-duty diesel: 885.9 MJ/100km).

The product mix of diesel and gasoline passenger vehicles (LD) is taken from [8] and is based on the average distribution between Jan. 2017 – Jan. 2018 in Germany. It consists of 66.7 % gasoline and 33.3 % diesel passenger cars. For heavy-duty a 100 % fossil diesel fleet is assumed as reference.

The CO_2 emissions of those vehicles are calculated on basis of the gasoline / diesel fuel consumption and on CO_2 conversion factors in accordance to the German “38. BImSchVO (§10)” [9] (gasoline: 93.3 gCO_2/MJ, diesel: 95.1 gCO_2/MJ).

For the vehicle depreciation of the fossil reference scenario the same depreciation for the diesel and gasoline vehicles is used as for the sustainable 100% scenarios.

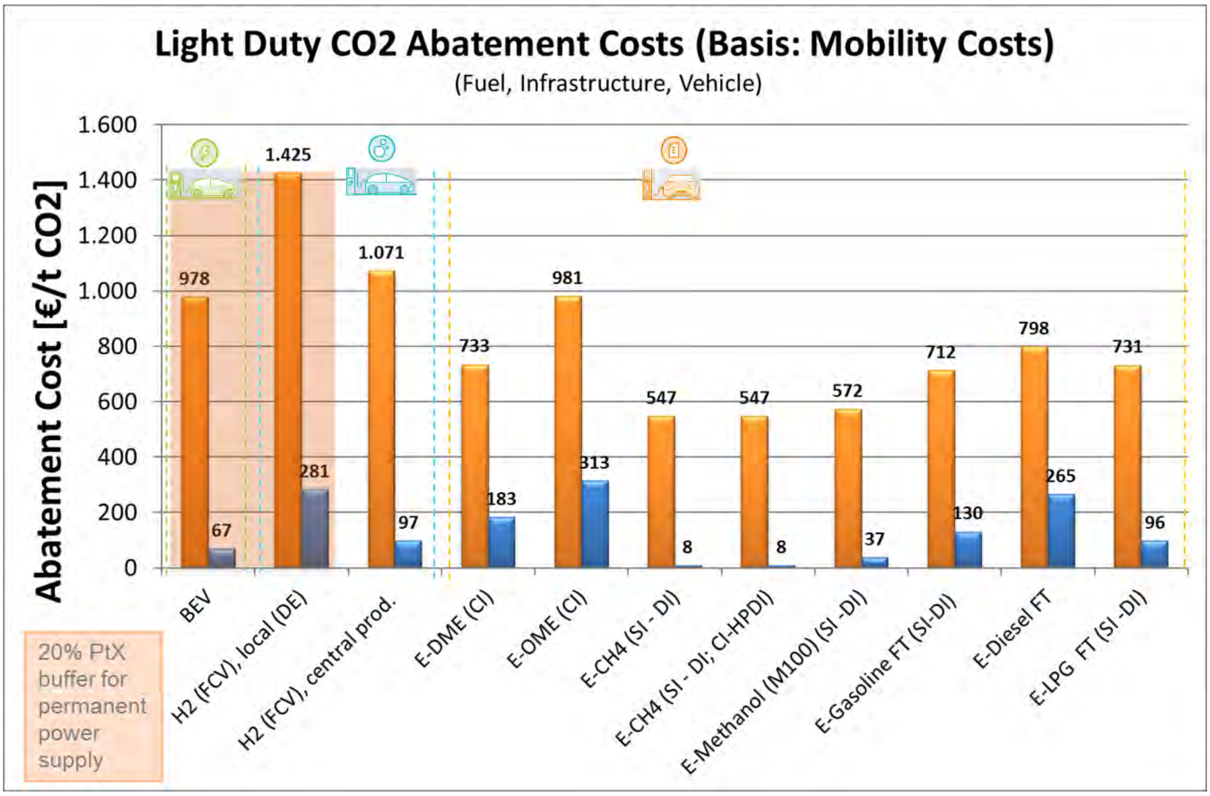

Figure 11: Passenger car (LD) CO_2 abatement costs (min. /max.)

The CO_2 abatement costs for passenger cars (light duty vehicles - LD) are displayed in **Figure 11**. The minimum LD CO_2 abatement costs can be achieved with e-methane at 8 €/tCO_2, which is 8.4 times lower than the minimum LD CO_2 abatement costs for BEV (67 €/tCO_2). A 50/50 e-FT-diesel/gasoline mix would require at least 197.5 €/tCO_2. The maximum abatement cost risk for BEV amounts to 978 €/tCO_2, which is 1.8 times higher than for e-methane (547 €/tCO_2) and 1.3 times higher than for a 50/50 e-FT-diesel/gasoline mix (755 €/tCO_2).

The CO_2 abatement costs for heavy-duty trucks are displayed in **Figure 12**. The minimum HD CO_2 abatement costs can be achieved with e-DME at 95 €/tCO_2, which is 1.8 times lower than the minimum HD CO_2 abatement costs for the (HO-) BEV pathway (168 €/tCO_2). A 50/50 e-FT-diesel/gasoline mix would require at least 213 €/tCO_2 (1.3 x (HO-) BEV). The maximum abatement cost risk for (HO-) BEV amounts to 739 €/tCO_2, which is 1.4 times higher than for e-methane HPDI (541 €/tCO_2), but only 90% of the abatement cost risk for a 50/50 e-FT-diesel/gasoline mix (815.5 €/tCO_2).

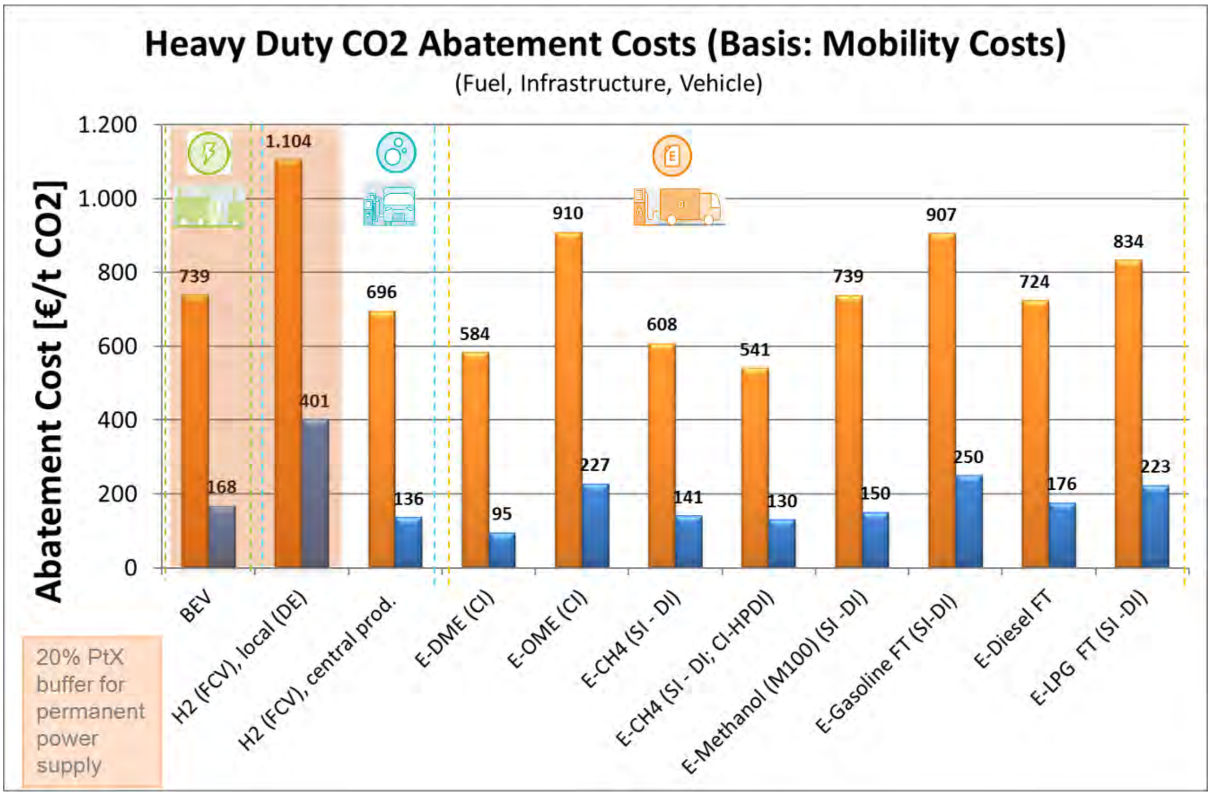

Figure 12: Truck (HD) CO_2 abatement costs (min. /max.)

Required Investment

Despite the high convergence of minimum costs, the scenarios differ in terms of investment needs, as shown in **Figure 13 and Figure 14** for some selected scenarios (e-FT diesel and e-FT gasoline already merged). All scenarios require significant investment into regenerative electrical power generation plants. In the minimum cost scenario, the investment demand ranges from € 89 billion (central hydrogen) over € 112 billion (BEV) and € 137 billion (methane) up to € 166 billion (FT diesel/gasoline). The power plant investment in the maximum cost scenario (cost risk) ranges from € 262 billion (BEV) over € 342 billion (H_2 central), € 526 billion (methane HPDI) and € 635 billion (FT diesel/gasoline) up to € 783 billion (OME).

	① Investment costs for power plants*	② Investment costs for fuel production	③ Investment costs for infrastructure	④ Cumul. add. vehicle costs** car (vs. gasoline) + truck (vs. diesel)
PtX	€137–526 bn (Pt-CH_4)	€102–118 bn (Pt-CH_4)	€3–6 bn (Pt-CH_4)	€0–122 bn + €24 bn (CH_4)
	€166–629 bn (Pt-MeOH)	€115–168 bn (Pt-MeOH)	< €1 bn (Pt-MeOH)	€0–20 bn + €0 bn (MeOH)
	€166–635 bn (Pt-FT)	€176–254 bn (Pt-FT)	€0 bn (Pt-FT)	€82 bn + €0 bn (FT)
	€149–570 bn (Pt-DME)	€103–151 bn (Pt-DME)	€1–2 bn (Pt-DME)	€163–231 bn + €1 bn (DME)
	€208–783 bn (Pt-OME)	€167–243 bn (Pt-OME)	< €1 bn (Pt-OME)	€163 bn + €0 bn (OME)
H_2	€89–342 bn (central)	€71–87 bn (central)	€19–38 bn (central)	€163–850 bn (car)
	€273 –568 bn (local)*	€55–66 bn (local)	€19–128 bn (local)	+ €37–125 bn (truck)
BEV	€112–262 bn*	0	€38–198 bn	€163–768 bn (car) + €52–88 bn (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)

Figure 13: Distribution of investment requirements by sector

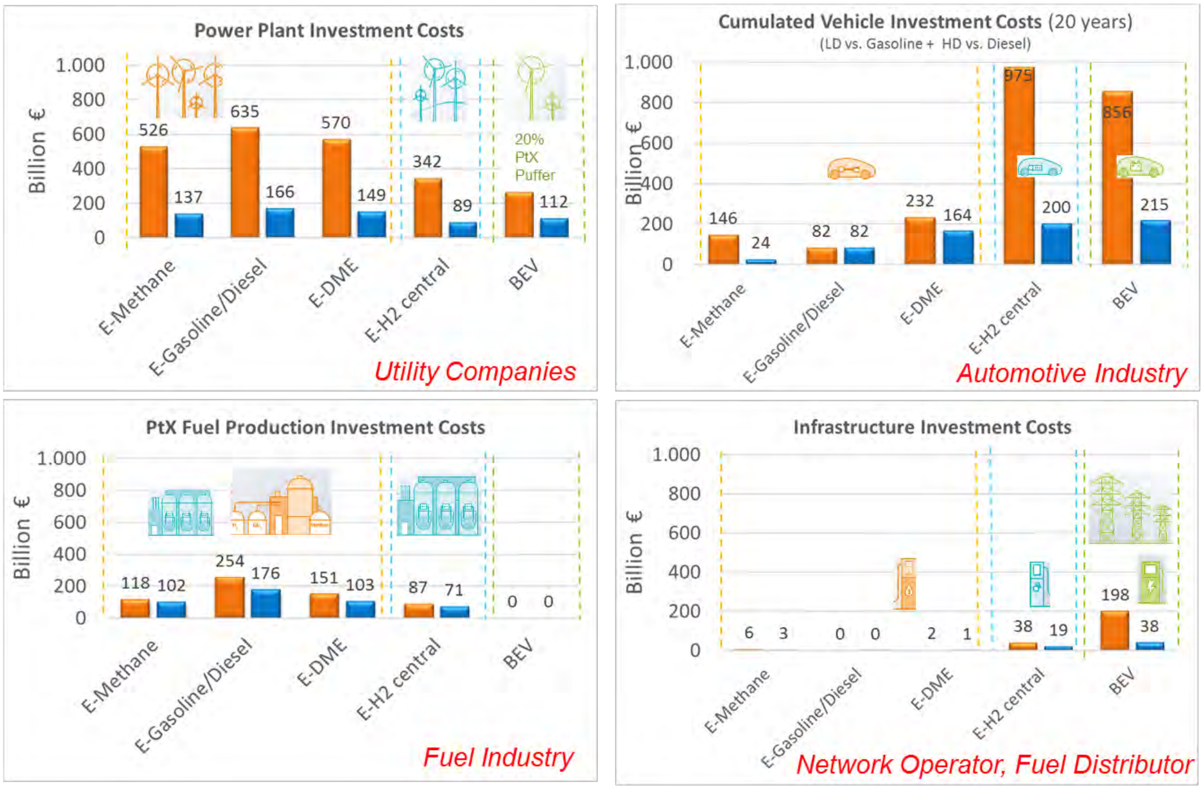

Figure 14: Distribution of investment requirements by sector

While the e-fuel scenarios require additional investment into the e-fuel production plants (from € 102 billion minimum costs for methane up to € 254 billion maximum costs for 50/50 FT diesel/gasoline), electro mobility needs significant investments into the distribution infrastructure (€ 38 – 198 billion incl. grid extension). Hydrogen (central production) requires investment into both sectors, fuel production (€ 71 – 87 billion) and distribution (€ 38 – 198 billion). The highest investment risk occurs on the vehicle side, when the vehicle on-costs vs. the gasoline passenger car and diesel truck are cumulated over 20 years. While the minimum cumulated vehicle on-costs for e-fuel pathways are in the range of € 0 – 164 billion, minimum cumulated BEV on-costs are at € 215 billion and FCEV on-costs are € 200 billion (assumption for passenger cars: BEV, FCEV and diesel vehicle cost parity). Considering the cost risk (maximum cost scenario), FCEV (€ 975 billion) and BEV (€ 856 billion) cumulated on-costs are considerably higher than those of e-fueled vehicles with combustion engines (€ 82 - 232 billion).

The total investment requirements (sum of the four sectors shown in **Figure 13 and 14**) of the selected pathways are shown in **Figure 15**.

Considering 100 % climate-neutral road transport, e-methane shows the lowest minimum investment requirement: up to € 266 billion are needed according to the results of the study. A 100 % battery electric fleet leads to a minimum investment of € 364 billion, closely followed by the most favorable fuel cell scenario with € 378 billion. The differences are considerably higher when the investment risks (maximum cost scenario) are taken into account. The highest investment risks arise for the hydrogen scenario (€ 1,442 billion) and the battery electric scenario (€ 1,317 billion). The lowest investment risks appear for e-methane (€ 796 billion) and e-methanol (€ 818 billion), followed by DME (€ 955 billion) and FT diesel/gasoline (€ 972 billion).

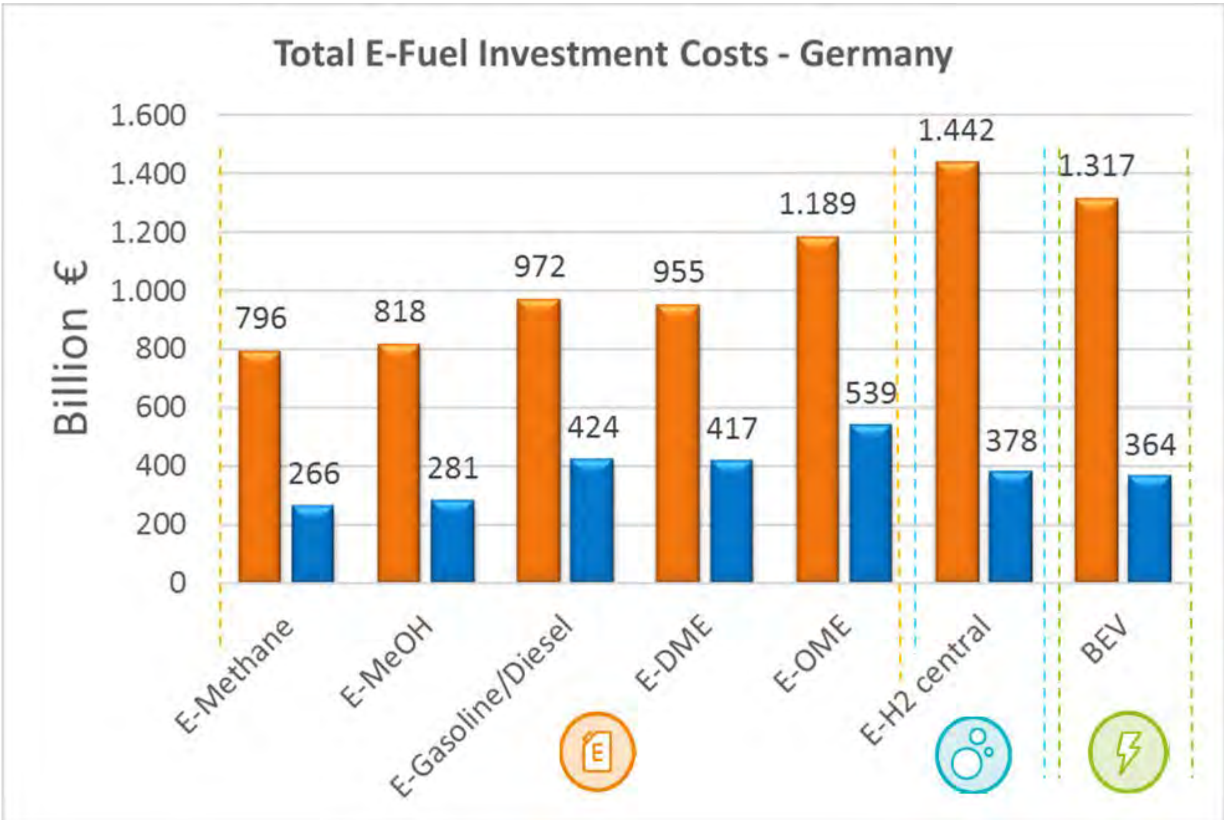

Figure 15: Total e-fuel investment requirement in Germany

Parameter Variation

Parameter variations have been carried out in order to investigate the impact of some key parameters, as CO_2 availability from sources, passenger car (LD) vehicle hybridization and cold-season operation (winter heating requirements)

CO_2 available
In a 100 % sustainable world, there will be hardly any other CO_2 source available than ambient air, in particular in the attractive high-yield MENA regions. However, for the transient period from fossil to sustainable energy there are many CO_2 sources available, which can be used instead of ambient air to feed the e-fuel production process. In order to simulate the best case, here called “CO_2 available”, the energy and cost for the CO_2 extraction out of ambient air are deliberately set to zero for 100 % of the e-fuel production.

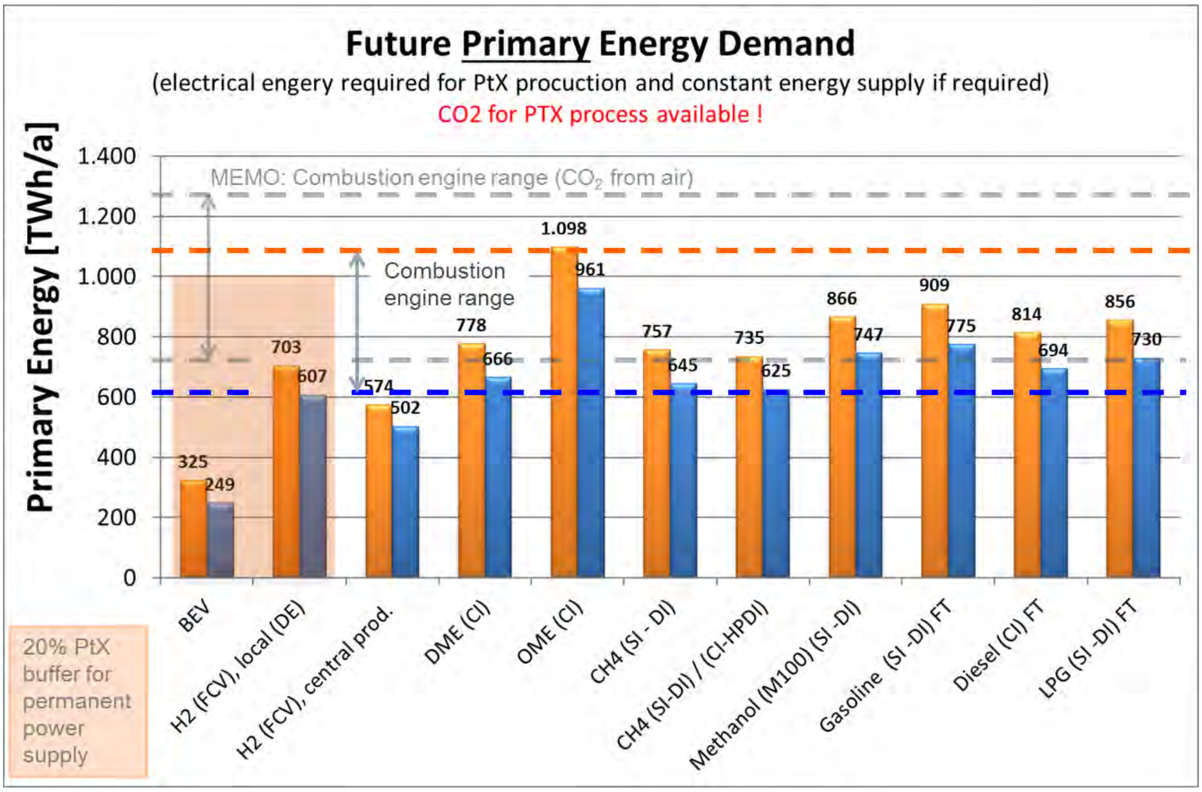

Figure 16: Annual primary energy demand (min. / max.) for variation“CO_2 available”

The effect of available CO_2 sources on the annual primary energy demand (Germany) is shown in **Figure 16**. The lowest primary energy demand is still achieved with the unchanged 100% BEV pathway. For the e-methane (HPDI) pathway, the primary energy demand is reduced by 16.8 % - 19.3 % (to 2.1 – 2.5 x BEV energy demand), for the e-FT-diesel/gasoline (50/50) pathway by 19.3 % - 21.9 % (to 2.7 – 3 x BEV energy demand), depending on the scenario. Thereby the BEV primary energy demand is still 7- 9% of the total primary energy demand in Germany 2015 (PE_{2015}) (3,632 TWh/a), and the e-H_2 (central) demand still 14-16% PE_{2015}. For the e-methane (HPDI) pathway, PE_{2015} is reduced from 21-24% (CO_2 from air) to 17-20% (CO_2 available), for the e-FT-diesel/gasoline (50/50) pathway from 26-29% (CO_2 from air) to 20-24% (CO_2 available).

In **Figure 17** the effect of available CO_2 on the mobility costs for passenger cars is displayed. With CO_2 from available sources, e-fuel mobility costs theoretically could be reduced by approximately 4 -10 %. The mobility cost benefit of the most cost efficient LD e-fuel (e-methane) to BEV would grow from 3 - 16 % to 8 - 23 %. Due to the limited (and unknown) availability of CO_2 sources other than ambient air in low-cost regions and the limited impact of the CO_2 source on the minimum mobility costs, available CO_2 is not considered in the remainder of this paper.

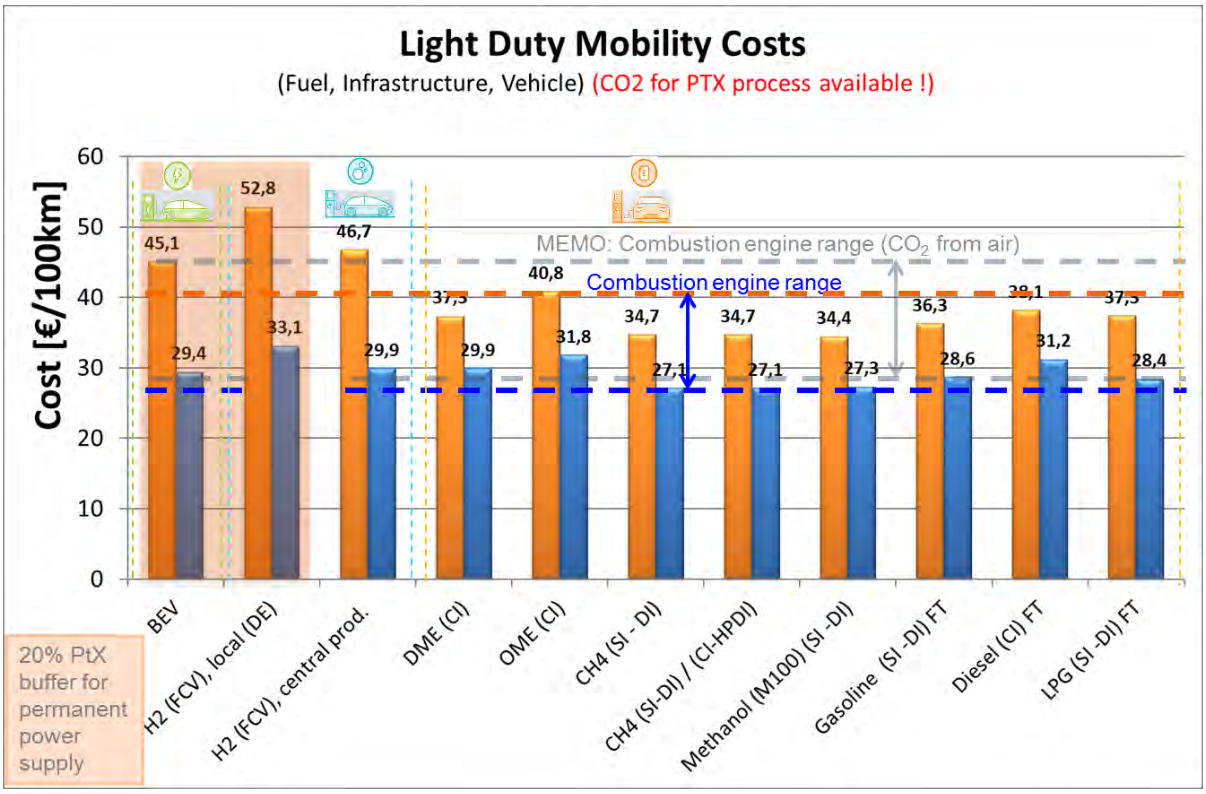

Figure 17: Mobility costs for passenger cars (min. /max.) for variation “CO_2 available”

Passenger car (LD) vehicle hybridization and cold-season operation

Within the original FVV study, the reference vehicle with combustion engine for each e-fuel pathway is not hybridized in order to enable a clear separation of technology effects. In reality, hybrid technology is already penetrating the vehicle market in considerable volumes and is expected to become a mainstream technology in the near future. Hybridization allows a vehicle with combustion engine to recuperate braking energy and to enable engine operation at more efficient conditions. Hybridization therefore helps to increase efficiency and to reduce fuel consumption, but it also increases the vehicle costs.

The level of hybridization can be very different, from micro hybridization (12 V, stop-start), over mild hybridization (48 V, small battery capacity) to full hybridization (high voltage system, larger battery capacity). The hybridization level has a strong impact on the efficiency benefit and vehicle on-costs. Furthermore, the efficiency benefit is strongly dependent on the applied operation conditions and the base vehicle.

For this study, an “average hybrid” has been defined. The fuel efficiency benefit is assumed to be 15 %, even if with full hybridization in a low loaded cycle up to 30 % benefit can be obtained. The on-costs are assumed in accordance to the RB Auto Oil Study [5] as average costs between a full hybrid and a mild hybrid. They amount to € 1,460 per vehicle (costs for the customer). The costs and efficiency assumptions for passenger car (LD) hybridization are summarized in **Table 3**.

	Min Cost Scenario (Hybrid)	Max Cost Scenario (Hybrid)
LD Vehicle Costs Basis: representative gasoline vehicle C-segment: Base price 20,000 € Depreciation according to ADAC - 15.000km/a - 4 years - 300 €/month Assumption: depreciation of customer on-costs direct proportional to depreciation of base price.	Assumption for 2050: cost parity of BEV and FCEV to diesel vehicle <u>(non-hybrid)</u>: • all SI concepts: no on-cost vs. gasoline vehicle • all CI concepts +2,400 € vs. SI • BEV500 und FCV: +2,400 € vs. SI Avg. Hybrid BEV500: (20.000 +2,400) € = 22,400 € FCEV (20,000 +2,400) € = 22,400 € **Gasoline: (20,000 +1,460) € = 21,460 €** DME (20,000 +2,400 +1,460) € = 23,860 € Diesel/OME (20,000 +2,400 +1,460) € = 23,860 € Methane (20,000 +1,460) € = 21,460 € Propane (20,000 +1,460) € = 21,460 € Methanol (20,000 +1,460) € = 21,460 €	On-cost according to **Roland Berger Auto-Oil Study** (2030) + 2018 OEM & retro fitter price lists (assumption: OME as Diesel, DME as Diesel + LPG tanks) Avg. Hybrid BEV500: (20,000 +11,300) € = 31,300 € FCEV: (20,000 +12,500) € = 32,500 € **Gasoline: (20,000 +1,460) € = 21,460 €** DME (20,000 +3,400 +1,460) € = 24,860 € Diesel/OME: (20,000 +2,400 +1,460) € = 23,860 € Methane (20,000 +1,800 +1,460) € = 23,260 € Propane (20,000 +1,500 +1,460) € = 22,960 € Methanol (20,000 + 300 +1,460) € = 21,760 €
	• Hybridization on-cost according to Roland Berger Auto-Oil Study (2030). Average of Mild Hybrid and Full Hybrid": 1,460 € • Hybridization efficiency benefit: Average "Mild & Full Hybrid": 15 %	

Table 3: Costs and efficiency assumptions for passenger car (LD) hybridization

Since vehicle efficiencies based on the NEDC cycle have been used to calculate the future energy demand of each investigated fuel-powertrain-pathway, the results do not consider any low temperature operation. In order to estimate the effect of cold-season operation in Germany, a simple approach is applied to the three main pathways BEV, FCEV and e-fuels, as summarized in **Table 4** and illustrated in **Figure 18**.

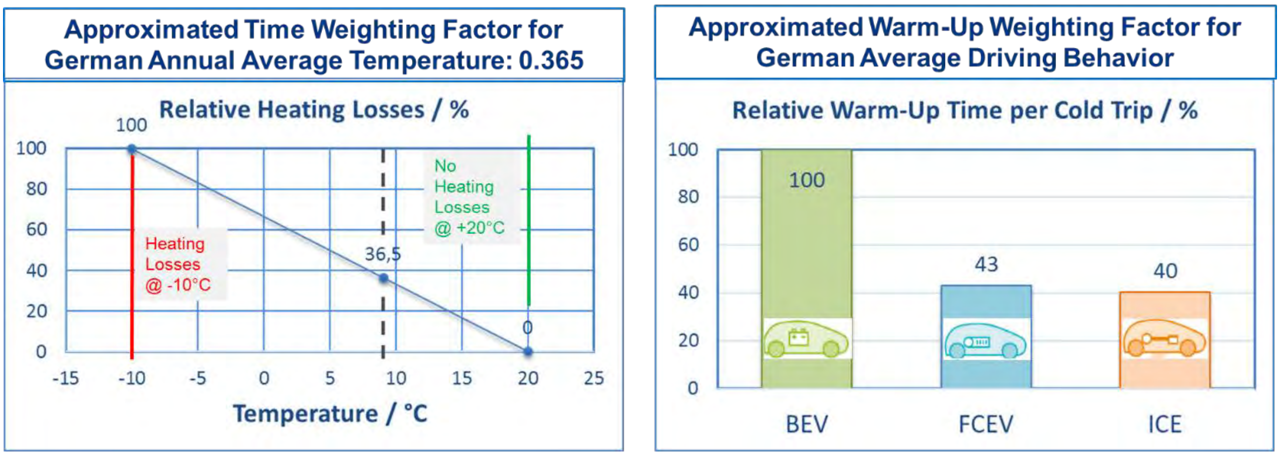

Figure 18 Approach to estimate effect of cold-season operation on efficiency (in Germany)

Pathway	Assumptions
All	Temperature basis for energy consumption in Fuel Matrix: 20°C (in accordance to NEDC conditions). Assessment of efficiency and cabin heating penalty at reference temperature of -10°C. Average Temperature Germany [10] : 9.05 °C → weighting factor between 20°C and -10°C operation: 0.365 Average trip distance/speed (motor-driven private transportation) [11] : 14.7 km / 42.2 km/h (3.4 trips /day) Average mileage per vehicle per year [12] : 14.416 km → 39.5 km/day → 0.926 driving hours / day Assumption: 2/3 of the daily trips require cold starts → 2.27 cold starts / day
BEV 	Losses for cabin heating (PTC) and battery heating at -10°C [13]: 42.1 % Permanent heating required at -10°C ambient temp. → time weighting factor: 1 Weighted efficiency reduction: 15.4 %
FCEV 	Losses for cabin heating (PTC), fuel cell and battery heating at -10°C: 19 % Heating time until PTC off (60°C FC temp.): 640 s → time weighting factor: 0.43 Weighted efficiency reduction: 3 %
E-Fuel 	Losses for cabin heating (PTC) at -10°C: 13 % Heating time until PTC off (engine warm): 600 s → time weighting factor: 0.40 Weighted efficiency reduction: 1.9 %

Table 4: Approach to estimate effect of cold-season operation on efficiency (in Germany)

The temperature basis for the energy consumption calculation in the Fuel Matrix is 20°C in accordance to the NEDC conditions. Additionally to those conditions, efficiency penalties are calculated for a 2nd operation point at -10°C for each of the three main pathways. The penalties consider the efficiency loss of the specific powertrain at cold conditions, as well as cabin heating requirements.

Afterwards a weighted average of the two efficiencies is calculated based on the annual average temperature in Germany (Berlin), which is 9.05 °C [10]. This results in a temperature weighting factor (between 20°C and -10°C operation) of 0.365 (**Figure 18**). For the average trip distance and speed for motor-driven private transportation ADAC data [11] are used for the estimation of the cold operation time (**Table 4**). In combination with the average mileage per vehicle and year [12] (14.416 km) the average daily driving distance (39.5 km/day) and driving time (0.926 hours / day) are calculated. With the aassumption, that 2/3 of the daily trips require cold starts, 2.27 cold starts per day are considered for each pathway. Depending on the daily number of cold starts and the duration of the additional (cabin and battery) heating requirement at -10°C, a relative activation time of the auxiliary heaters is calculated as shown in **Figure 18** (relative warm-up time per cold trip).

According to [13] the BEV efficiency is reduced by 42.1 % at -10°C. Additional energy is required to warm up the battery and the passenger cabin. Both energies are assumed to be required during the complete driving time of the electric vehicle. Therefore, the time weighting factor is set to 1 and the annually weighted efficiency reduction results into 15.4 % for a BEV.

Those numbers are valid for an electric vehicle with PTC heating device. In some of the existing and upcoming BEV, a heating pump is applied instead of PTC, resulting in an efficiency gain in cold-season operation. That additional potential is not regarded in the following comparisons, because public on-cost information for such heating pump systems has not been available, but would have been required for the calculation of the mobility costs, CO_2 abatement costs and investment costs. Furthermore, the FCEV and the ICE vehicles used for the comparison are equipped with PTC heaters as well.

The additional efficiency losses compared to NEDC conditions for FCEV operation at -10°C are assumed to be in the range of 19 %. Different to BEV operation, the fuel cell in an FCEV produces excessive heat during operation, which can be used for cabin heating once the fuel cell is warmed up. The PTC heating requirement is assumed to stop at 60°C fuel cell temperature, expected to be reached at about 640s after the start at -10°C. This results into a time weighting factor of 0.43 and a total weighted efficiency reduction of 3 % for an FCEV.

For a hybrid ICE vehicle, the cabin heating losses (heating supported via PTC) at -10°C are assumed to be 13 %. The additional heating time (PTC on) is assumed to end after approximately 600 s when the engine is warm. This results into a time weighting factor of 0.40 and a total weighted efficiency reduction of 1.9 % for an e-fueled vehicle with ICE vs. NEDC conditions.

Figure 19 displays the annual primary energy demand for the parameter variation "average passenger car (LD) vehicle hybridization plus cold-season operation". The truck (HD) characteristics are not changed, because hybridization benefits are negligible for long distance transportation and cabin heating losses relative to the required driving power are significantly lower than for passenger cars and light-duty commercial vehicles.

Due to the cold-season operation requirements the primary energy demand for BEV rises from 7-9 % PE_{2015} to 8-10% PE_{2015} (PE_{2015}: Total Primary Energy Demand Germany 2015). The FCEV pathway with central e-H_2 production remains at 14-16% PE_{2015}. For e-methane (HPDI) PE_{2015} is reduced from 21-24% to 19-22% and for e-FT-diesel/gasoline$_{(50/50)}$ from 26-29% to 23-26% PE_{2015}. For the e-fuel-ICE pathways the cold-season penalty is overcompensated by the average hybridization effect.

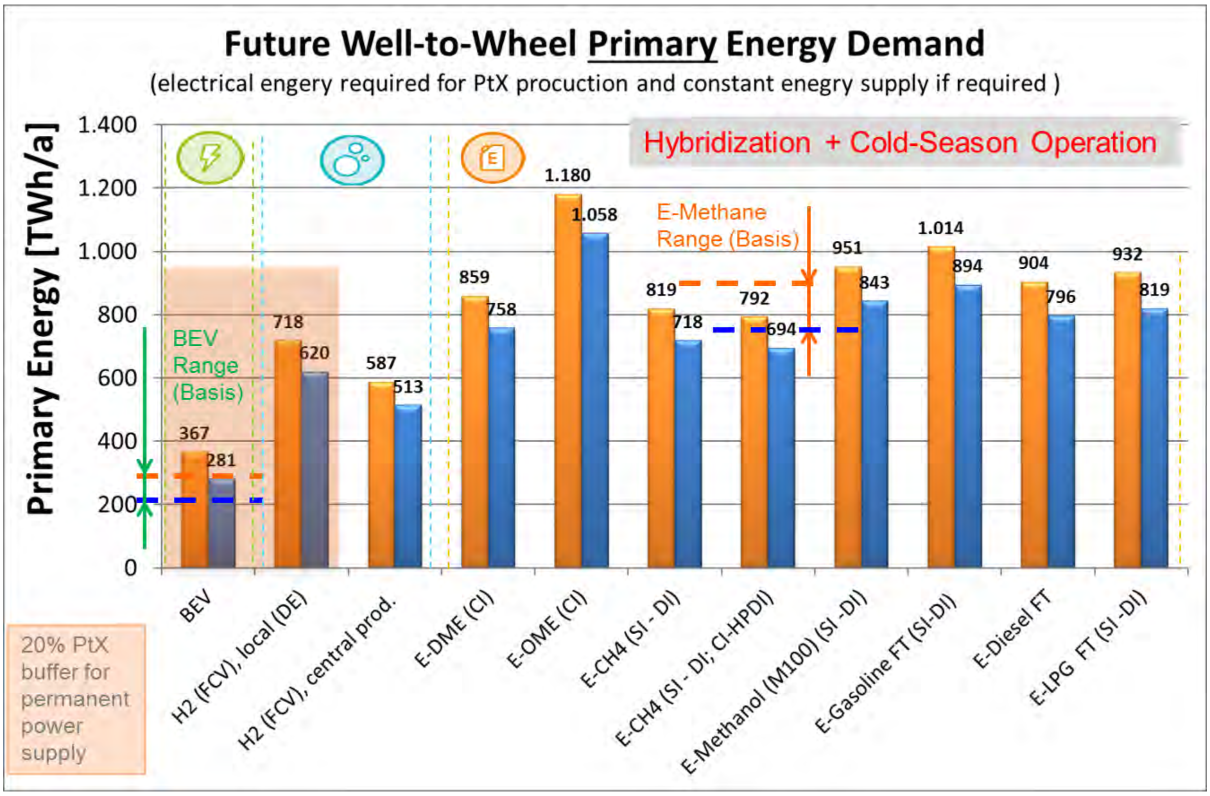

Figure 19 Primary energy demand for "Avg. LD hybridization and cold-season operation"

Figure 20 shows the “parameter-walk” “basis – LD hybrid – LD cold-season operation” with regard to the primary energy demand (LD + HD) of 2 exemplary ICE pathways (methane and 50/50 FT diesel/gasoline) and the central H_2-FCEV pathway relative to the BEV pathway. At the end of the walk, the FCEV pathway requires 1.6 – 1.8 times as much primary energy as a BEV, the e-methane (HPDI) pathway 2.1 – 2.5 times and the e-FT-diesel/gasoline$_{(50/50)}$ pathway 2.6 – 3.0 times.

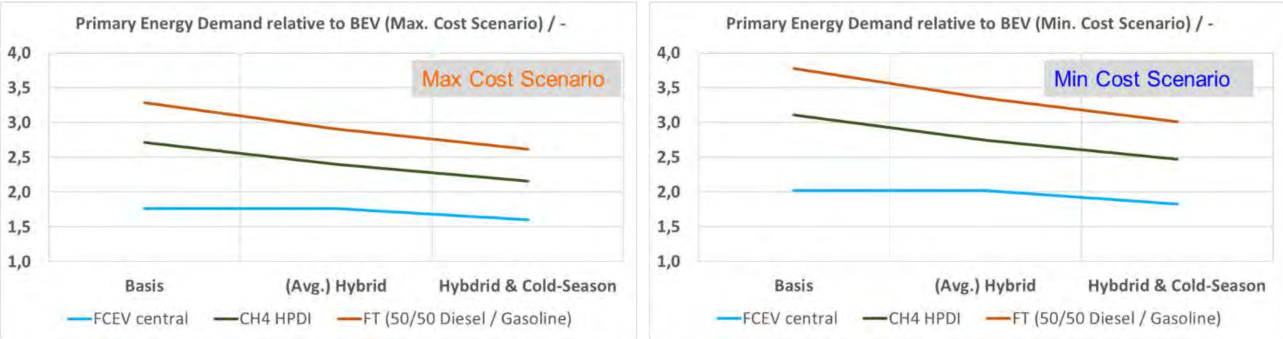

Figure 20 Primary energy demand - relative to BEV: “LD hybrid - cold-season walk”

Figure 21 shows the LD walk “basis – LD hybrid – LD cold-season operation” with regard to mobility costs relative to the BEV pathway. While in the maximum cost scenario hybridization leads to lower ICE mobility costs, the mobility costs of ICEs increase slightly with hybridization in the minimum cost scenario. Hybridization represents a significant cost share of the total vehicle costs in the considered reference vehicle and cannot be completely compensated by the resulting fuel saving costs without the consideration of fuel taxation. Cold-season operation leads to a reduction of the gap of mobility costs between BEV and the three other pathways (2x ICE and FCEV). At the end of the walk the FCEV pathway is at the same mobility cost level as the BEV pathway (factor 1.01 -1.02), e-methane (HPDI) can be up to 20 % cheaper (factor 0.82 – 0.99), the e-FT-diesel/gasoline$_{(50/50)}$ can be slightly cheaper, but also a little more expensive than the BEV pathway (factor 0.89 – 1.10).

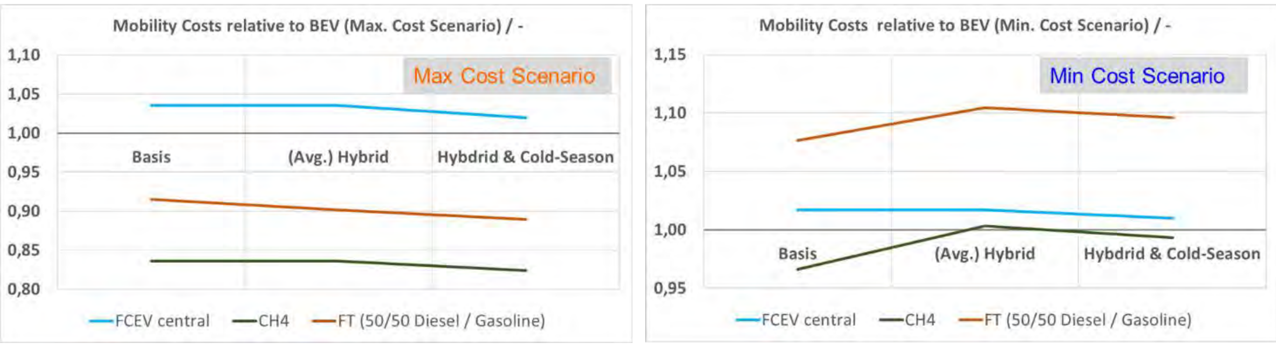

Figure 21 Mobility costs - relative to BEV: “LD hybrid - cold-season walk””

Figure 22 shows the walk “basis – LD hybrid – LD cold-season operation” with regard to CO_2 abatement costs relative to the BEV pathway. The CO_2 abatement costs behave very similar to the mobility costs. Like for mobility costs, in the maximum cost scenario hybridization leads to lower ICE CO_2 abatement costs, while the CO_2 abatement costs of ICEs increase slightly with hybridization in the minimum cost scenario. Cold-season operation leads to a reduction of the gap of CO_2 abatement costs between BEV and the three other pathways (2x ICE and FCEV). At the end of the walk, the FCEV pathway requires as much as 1.06 – 1.16 times of the CO_2 abatement costs of the BEV pathway. E-methane can be up to about 45 % cheaper (factor 0.55 – 0.86), while the e-FT-diesel/gasoline$_{(50/50)}$ can be up to about 30 % cheaper, but also more expensive than the BEV (factor 0.72 – 2.85), depending on the scenario.

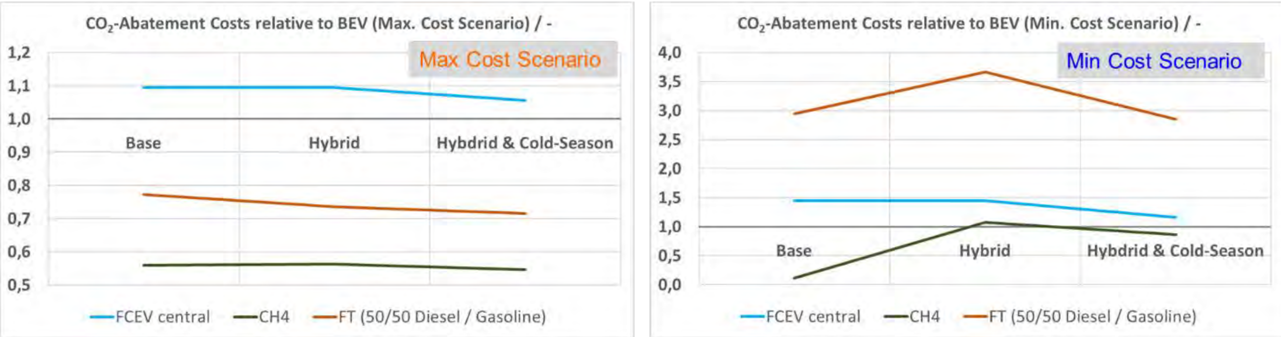

Figure 22 CO_2 Abatement costs - relative to BEV "LD hybrid - cold-season walk"

Figure 23 shows the walk "basis – LD hybrid – LD cold-season operation" with regard to required total investment relative to the BEV pathway. In the minimum cost scenario, the required total investment rises significantly with the introduction of hybrid technology for ICE. Because of the lower level of basis vehicle costs and the significantly lower fuel costs (without taxes) in the minimum cost scenario, the impact of the on-cost for hybridization has a bigger impact on the 20 years cumulated vehicle costs than in the maximum cost scenario. Cold-season operation leads to a reduction of the gap of required total investment between BEV and the three other pathways (2x ICE and FCEV). At the end of the walk, the FCEV pathway requires as much as 1.00 – 1.07 times of the total investment of the BEV pathway, while the ICE pathways can be significantly cheaper in the maximum cost scenario. e-methane (HPDI) can be up to about 40 % cheaper (factor 0.61 – 0.89), while the e-FT-diesel/gasoline$_{(50/50)}$ can be up to about 30 % cheaper, but also more expensive than BEV (factor 0.72 – 1.28), depending on the scenario.

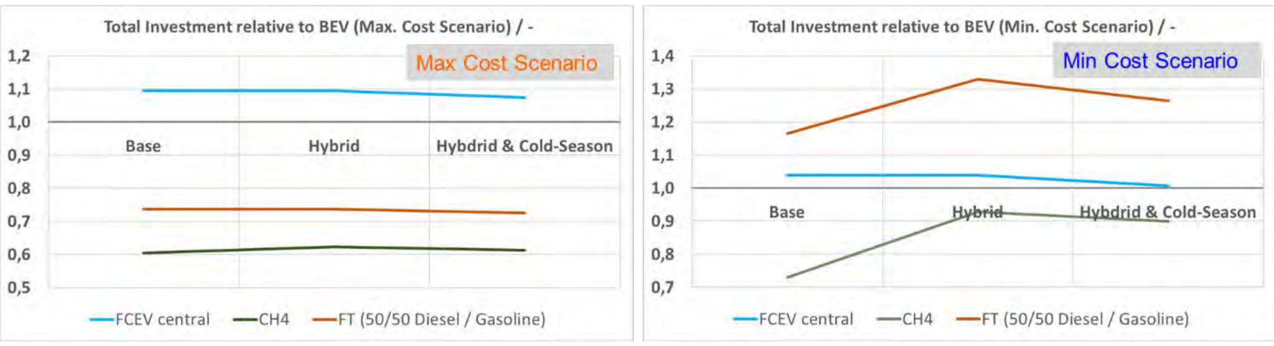

Figure 23 CO_2 Investment requirement - relative to BEV: "LD hybrid - cold-season walk"

Market Acceptance

Whether investments in a particular technology pathway 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 seconds. In all other scenarios, this time interval is less than 30 seconds. For certain applications, e.g. with high power density demands and without connection to the electrical grid, powertrains which contain a combustion engine or a fuel cell seem inevitable.

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: for e-methane, as well as for gasoline, diesel and LPG, which are obtained for example via Fischer-Tropsch synthesis. The existing fuel standards allow the admixture of 2 vol % hydrogen into CNG. e-methanol blending into gasoline is currently limited to 3 vol %.

Beside costs and market compatibility, certainly local emission limits are a very important criterion to meet. While local zero emissions are only achievable with BEV, FCEV and PHEV (plug-in hybrid vehicles), Zero-Impact-Emission-Mobility is assessed to be achievable with all of the investigated combustion engine concepts. Thereby “zero-impact” means, exhaust gas emissions are below the accuracy limit of the available detection methods and the environmental impact is below allowed immission limits according to BImSch(G) (Bundesimmissionsschutzgesetz).

Outlook

From a technology neutrality standpoint, all assessed pathways enable climate-neutral mobility. In this context, e-fuels would be able to achieve a competitive position in terms of mobility costs.

Although these 100 % scenarios are theoretical and relatively unrealistic, they are very useful tools for analyzing technology potential and comparing technical and economic suitability. The described conclusions do not merely reflect the opinion of a single industry partner involved in the study, but are rather to be viewed as the cross-industry synthesis of this joint study.

The very detailed calculation tool developed in the course of the study can be used for mixed scenarios to be investigated in the future.

Direct electrification (BEV) comes along with the lowest primary energy demand. The primary energy demand for an e-fuel transportation system is 2 to 3 times higher than for direct electrification (when efficient e-fuels are used). Therefore, direct electrification is recommended to be used where it is economically sensible and where customer requirements are met.

The calculation of the mobility costs shows, that the vehicle costs dominate considerably over the spending needed for the production and distribution of the energy carriers. In particular for battery electric vehicles (BEV) and fuel cell vehicles (FCEV) the future vehicle costs are very difficult to predict, which causes a high degree of uncertainty to future mobility costs for the customer. However, the cost risks for production and distribution also differ considerably depending on the pathway.

As mobility costs nearly converge for all considered energy pathways (when the high range of uncertainty of the predictions is considered), technology decision will be based on end customer requirements like driving range, charging time, usability, flexibility, comfort or resale value.

Long distance transportation and high power demand require higher energy densities and larger battery capacities, which rises the cost risk of the direct electrification pathway. The study is based on a 500 km electric range for battery electric passenger cars. For those applications as well as for heavy duty, e-fuels are a viable solution, since some of the considered e-fuels options provide a better economic efficiency, as the lowest CO_2 abatement cost opportunity and up to 40 % lower investment cost than direct electrification.

In addition, the high convenience and practicability, the abroad production option and import potential make e-fuels a perfect partner for directly electrified mobility, even if direct electrification is more energy efficient.

Legal boundary conditions for the economic implementation of e-fuels, as e.g. CO_2 crediting, are currently not given and need to be defined in order to enable e-fuel market penetration.

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