

FVV PRIME MOVERS. TECHNOLOGIES.

Energy paths for road transport in the future

Options for climate-neutral mobility in 2050





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“All roads lead to Rome” is a well-known proverb. And this proverb is based on a truth: 2,000 years ago, more than 370 main roads linked the Roman provinces together. The trade practiced along these roads formed the basis upon which the ancient Romans built their culture. Today, this proverb is also extremely valid, with the mobility of people and goods forming the spine of a successful economy. Despite this, it is no longer appropriate to carry on in the same vein as in the past. It will only be possible to achieve the climate goals outlined in the Paris Climate Agreement from 2015 by implementing countermeasures in a courageous fashion. To do so, road transport will predominantly have to be converted to climate-neutral energy paths by the year 2050.

However, simply focusing on vehicle propulsion systems will not be enough. We will only begin to properly protect our atmosphere when we achieve climate neutrality throughout the entire energy chain. Therefore, under the direction of Dr. Ulrich Kramer (Ford), a working group at the Research Association for Combustion Engines (FVV) has analyzed different energy paths in great detail. The study examines the use of electricity, hydrogen and synthetic e-fuels as energy sources in road transport from both a technical and an economic point of view. For the first time, valid estimations for the investments required for different options across the entire energy chain have been provided from an engineering standpoint. This briefing paper summarizes the main results and provides a foundation for a fact-based dialog on the energy sources and power-train systems of the future. This much can be said in advance: The proverb rings true here as well, with not just a single path leading to the goal, but rather a clever combination of different energy paths.

We would like to thank the working group, in which more than 40 experts from the cross-sector innovation network of the FVV were involved at one time or another, as well as Dr. Kramer for their commitment, and would like to say that we are greatly looking forward to a productive discussion of the results.

SEITE 6-9
Objectives

One goal, several paths	6
100% renewable – but how?	8

SEITE 10 – 15
100 % Scenarios

SEITE 16 – 20
Conclusions

The “100 % electric” scenario	10	Comparison of costs and investment	16
The “100 % hydrogen” scenario	12	Climate protection and market acceptance	18
The “100 % e-fuels” scenario	14	Outlook	20

One goal, several paths

In December 2015, the international community agreed upon a joint climate protection goal. The aim was to slow down greenhouse gas emissions and ensure that the average temperature increase due to global warming is a maximum of two degrees Celsius by 2100, and ideally well below 1.5 degrees Celsius. These goals can only be achieved if the transport sector becomes predominantly climate-neutral by the middle of the century.

The goal is clear: Road transport must become predominantly climate-neutral by 2050. When discussing which path leads to the goal, two conditions must be observed:

An observation which only looks at the CO₂ emissions from the vehicles is insufficient. Even if the CO₂ emissions of a single vehicle reach the target of zero, greenhouse gases may well still be produced during the production and transportation of the energy source used in the vehicle. Complete climate neutrality can therefore only be achieved by expanding the scope and including emissions from energy provision and distribution. An observation of this type is known as a “well-to-wheel” analysis, as it takes the entire energy chain into account, from the source (the “well”) all the way to the wheel. The manufacture and scrapping of plants and vehicles, which are part of a complete life cycle analysis, are not regarded in this study.

Furthermore, the greenhouse gas emissions in 2050 or 2100 are not decisive for the climate change that actually occurs, but rather the amount of the CO₂ introduced into the atmosphere by that time. To borrow a term from mathematics, the value here is the integral of all individual emission values. The

goal of a responsible control measure must therefore be to make a decision on how to implement climate-neutral energy sources in the transport sector as soon as possible. The study includes detailed analyses of the technical degree of maturity and the potential for market introduction of the different paths, thus taking this aspect into consideration.

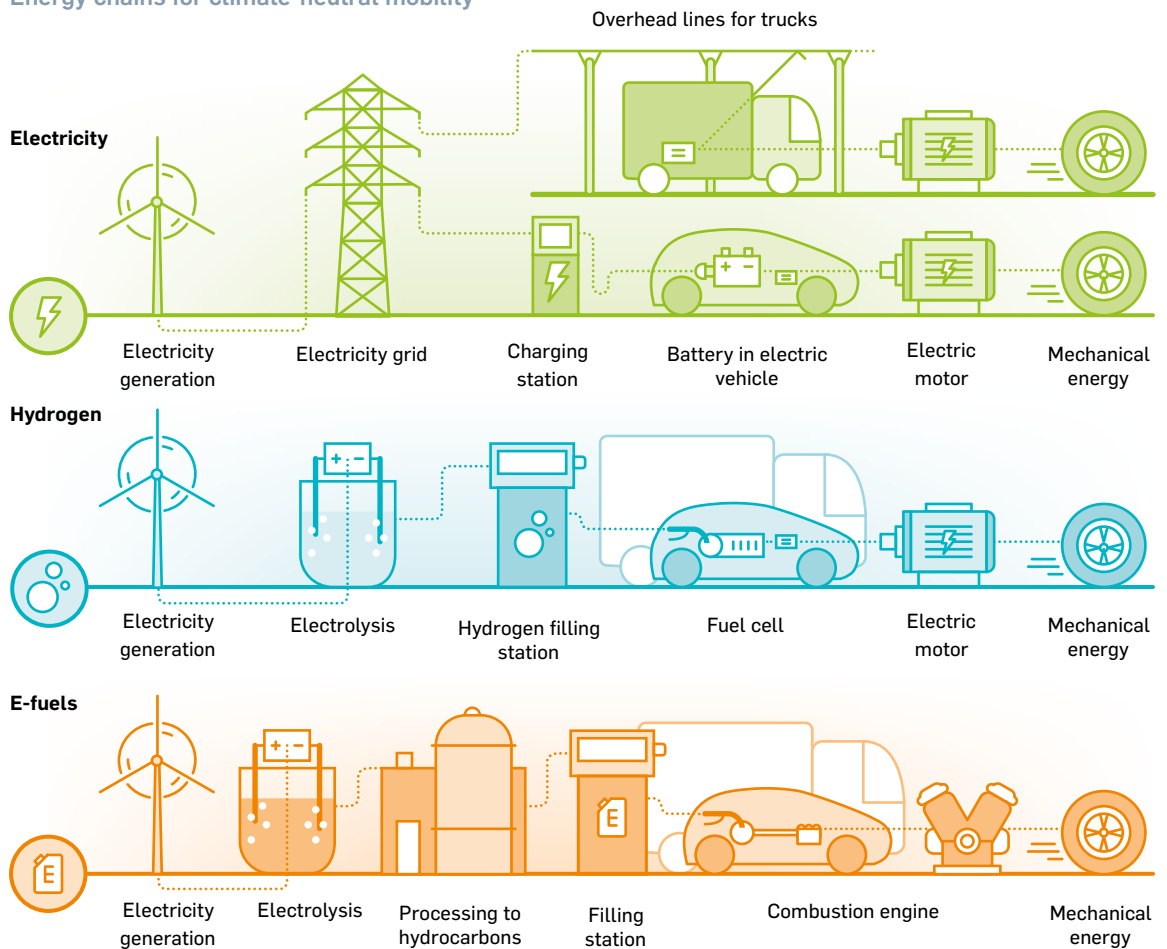
Completely greenhouse gas-neutral mobility can only be achieved if renewable energies can successfully be used in the transport sector. Realistically, the high energy requirements can only be covered by using generation methods that already exist today, in particular solar and wind energy. Renewable electricity as an energy source will therefore always be at the start of the energy chain. The electrification of road transport, the introduction of which has already begun, is therefore sensible and unavoidable. The main question of the FVV study is therefore not whether using electricity in road traffic is sensible, but how electrical energy should be used in mobile applications. From a technological standpoint, three paths are available to achieve this goal:

1. The electricity is stored electrochemically and directly in the vehicle using a charging infrastructure and batteries and is then used for

- propelling the vehicle via an electric motor.
- Hydrogen is produced from the electricity via electrolysis. This is transferred from a hydrogen filling station to the vehicle, where a fuel cell creates electricity for the electric motor.
 - The hydrogen created through electrolysis is enriched with carbon from CO₂ in a closed CO₂ loop. Through this process, gaseous or liquid fuels (known as "e-fuels") are created, which can be distributed across the existing filling station infrastructure and then used to generate mechanical energy in combustion engines.

The goal of the study is to analyze the costs related to the implementation of the three paths and, on the basis of this, estimate the required level of investment and define the need for research. Other criteria which are relevant for the implementation are also taken into account, such as safety or the expected market acceptance.

Energy chains for climate-neutral mobility



100 % renewable – but how?

There is now a large number of studies on the transition of the transport sector towards the use of renewable energy sources. The methods used in the majority of these studies are based on certain assumptions on the costs for energy sources and powertrain systems, traffic volume, efficiency rates and numerous other parameters, which are then calculated for the different market shares of the propulsion systems and energy sources. The results diverge depending on the weighting of the parameters and which market shares are used, which is why the FVV deliberately decided on a different approach.

For this study, representatives of automobile manufacturers and suppliers, energy and mineral oil companies, the chemical industry and various associations pooled their knowledge on the individual technologies. During this process, both technical and economic aspects were taken into account and consolidated in a working group. Contributing experts from different sectors developed comparable scenarios for all relevant criteria, in particular the overall energy requirement and mobility costs, which take into account the costs of energy provision and distribution, as well as vehicle costs. The framework conditions for each scenario are identical, which means that energy requirements and mobility costs can be directly compared. The long-term potential for technical development and therefore the achievable degree of efficiency can only be estimated for almost all steps of the energy transition. Minimum and maximum costs were defined to cover the remaining uncertainties.

The method used in the study consciously employs fictitious 100 % scenarios, for which a market share of 100 % in 2050 was assumed:

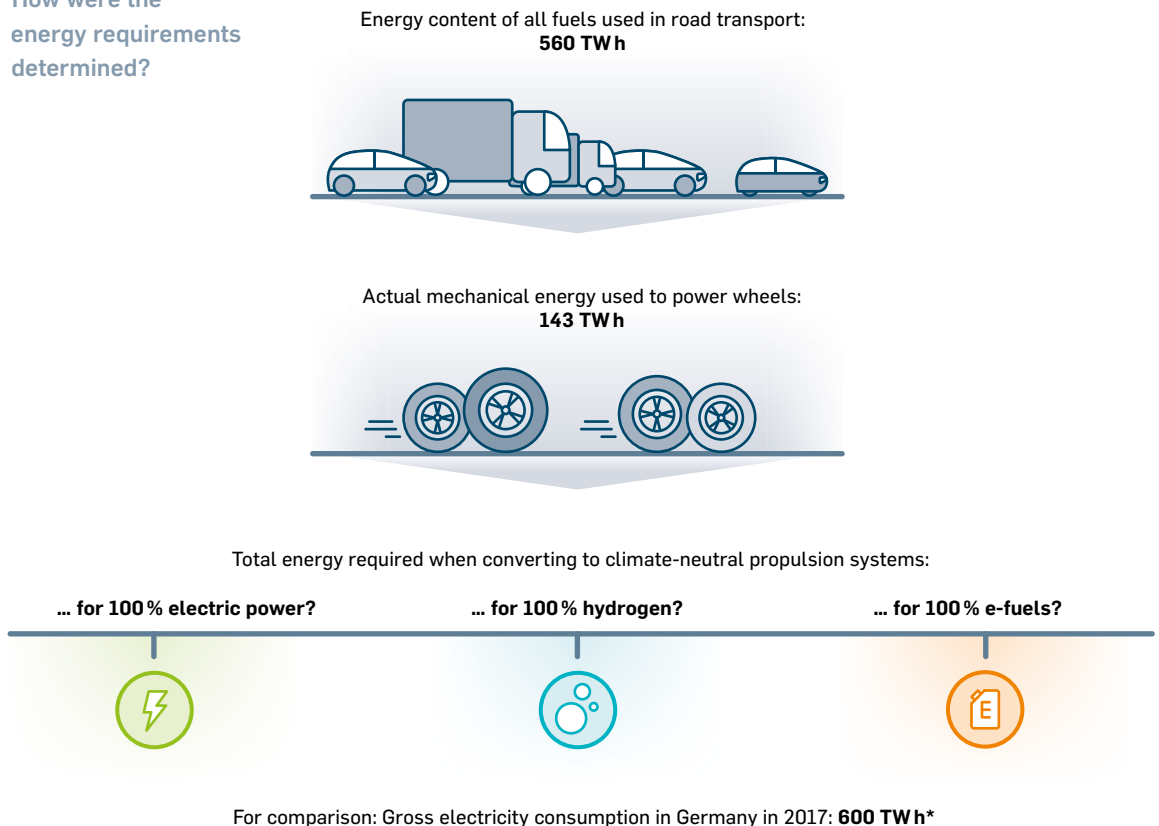
- 100 % electric: Only battery electric vehicles are used. For long-distance truck transportation, this scenario includes the installation of overhead lines on the highways.
- 100 % hydrogen: The energy transformation takes place in the vehicle via a fuel cell.
- 100 % e-fuels: Calculations were made for 100 % scenarios for eight fuels from power-to-x plants.

The results from these calculations will also be available in the future for the calculation of mixed scenarios, in which different market shares of the powertrain types, hybrid drives and fuel additives will be considered. The reduction of greenhouse gas emissions using biofuels was intentionally excluded in the study as a 100 % scenario is very unlikely due to the limited availability of biomass. However, biogenic fuels (both liquid and gaseous) could play an important role in ensuring that road traffic becomes climate-neutral in the probable mixed scenarios. The starting point for all of the results from this study is the energy required for mechanical movement – i. e. to drive the wheels. The basis is provided by the

calculation of the energy content of the fuel used in Germany in 2015 (560 TWh, of which 440 TWh were used in cars and 120 TWh were used in trucks), which has been applied to the current number of vehicles. Taking current powertrain efficiency into account, the total German “wheel energy requirement” is 143 TWh. For all three 100 % scenarios, the energy requirement was then calculated backwards while taking into account all efficiency losses in the whole energy chain back to the generation of the electricity. This simplified process consciously

eliminates the influence of non-technical factors, such as reduced annual mileage or a lower number of vehicles due to changed mobility behavior. Other clear efficiency increases through hybridization of combustion engine concepts were not yet taken into consideration in this study. However, because over the course of the study a calculation tool was created that takes these factors into account, a foundation exists for conducting additional parameter variations.

How were the energy requirements determined?



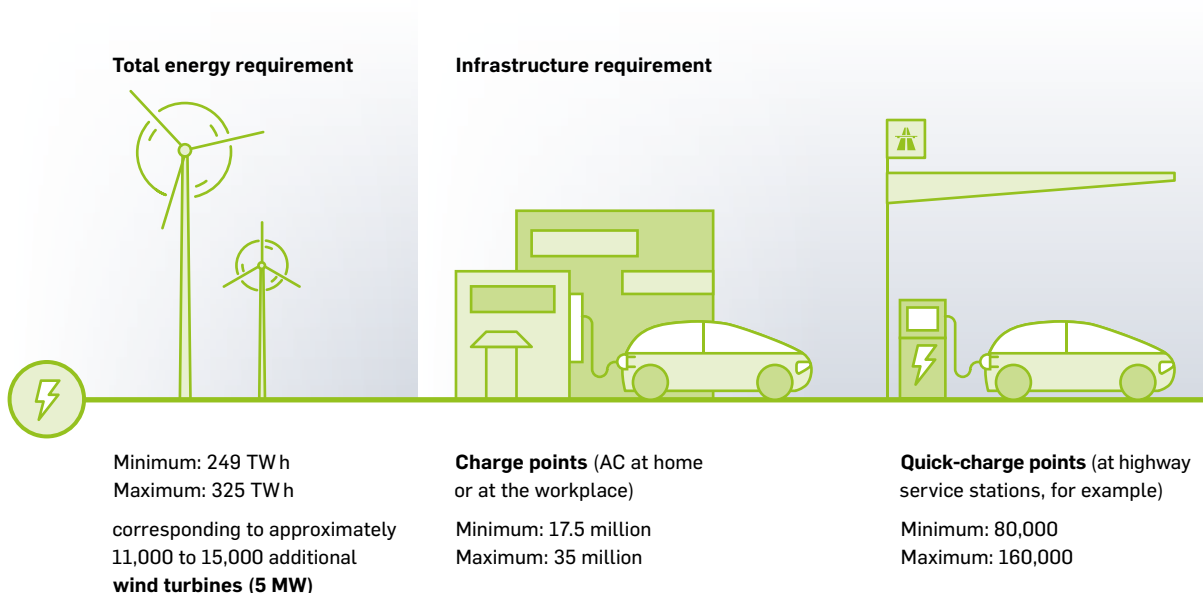
*Source: Arbeitsgemeinschaft Energiebilanzen (AGEB – Energy Balances Group)

The "100% electric" scenario

Should we succeed in using regeneratively produced electricity directly in the vehicle, this path should always be preferred from the standpoint of energy efficiency, as a large part of conversion losses that occur when using chemical storage are avoided. The reference scenario used in the study is therefore the 100% electrification of all vehicles by 2050.

If we take the remaining efficiency losses on the purely battery electric path into account, the total electric energy requirement in this scenario is at least 249 TWh per year, and at most 325 TWh per year. This corresponds to approximately half of the current total German requirement of electrical energy. In later comparisons with other scenarios, however, it must be considered that this value does not include the energy required to heat and cool the interior, a figure which in practice could comprise

up to one third of the total vehicle energy requirement. This value does, however, include the losses incurred when transporting electricity to the charging point and during charging, with figures ranging from 6% to a maximum of 28% incurred only during fast charging. The 100% electric scenario assumes that electricity must be available at all times, as neither the vehicles nor the charging stations can store enough electricity to cover common "dark periods" (no wind or sun) – i.e. times without noteworthy



electricity production from regenerative sources. Instead, it shall be assumed that around 20 % of the electricity required to operate a vehicle is produced in gas power plants, which are operated in a climate-neutral manner using gas on the basis of renewable electricity (power-to-gas). This is reflected in the electricity system costs. Despite this, due to the high degree of efficiency, the route-related energy costs for cars are between 1.99 euros and 4.68 euros per 100 kilometers and are thus lower than all other paths.

In this scenario, trucks are operated using a combination of batteries and overhead lines ("hybrid-overhead line trucks"). In this case, a minimum of 4,000 km and a maximum of 13,000 km of German highways are equipped with overhead lines. Goods transport trucks on non-highway roads are powered using batteries which are charged during journeys along routes equipped with overhead lines.

In order to estimate the economic investment requirement for a 100 % electric scenario, the costs involved in expanding the electricity distribution infrastructure are also of significant importance. The extent to which expansion is required depends on the degree to which energy production can occur decentrally

in the future. The considerable total energy requirement does, however, call for a large share of centralized production in offshore wind farms in the North Sea and the Baltic Sea. Furthermore, the ability to control the time spent on charging processes provides significant leverage as it impacts the connected load of the local network transformers and thus the size of the distribution networks. This study assumes that between 0 and 98 billion euros must be invested in the electricity grid infrastructure, whereby up to 21 billion euros would be needed for the installation of overhead lines for road freight transport. The additional costs of the charging infrastructure must be taken into account for cars. For a 100 % scenario, the experts in the working group assume that a minimum of 80,000 and a maximum of 160,000 quick-charge points are needed, as well as between 17.5 million and 35 million AC charging points at the home and at the workplace.



Overhead lines for trucks

on German highways:

Minimum: 4,000 km

Maximum: 13,000 km

Potential expansion of the **electricity grids** costing up to 77 billion euros

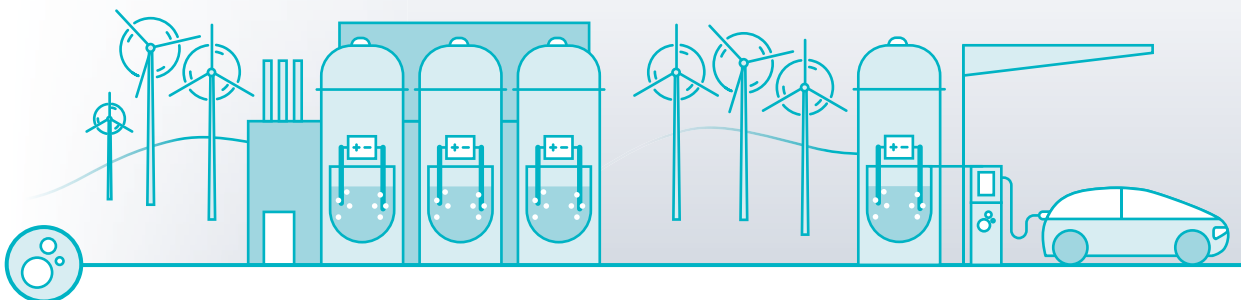
The “100 % hydrogen” scenario

The technological advances of the last three decades, both with regard to electrolysis and particularly fuel cells, have made the use of hydrogen as an energy source for the transport sector a conceivable idea in the foreseeable future. The hydrogen path combines high efficiency levels with a good storage capability.

It is fundamentally possible to produce hydrogen on an industrial scale by means of electrolysis, with an efficiency of up to 73 %. The good storage and transportation capabilities of hydrogen over very long distances compared to electricity mean that

the required production plants can be installed in countries with significantly higher solar radiation, which in turn results in lower manufacturing costs.

Total energy requirement



For **centralized electrolysis**

Minimum: 502 TWh

Maximum: 574 TWh

corresponding to approximately
23,000 to 26,000 additional
wind turbines (5 MW)

For **decentralized electrolysis** at the filling station

Minimum: 607 TWh

Maximum: 703 TWh

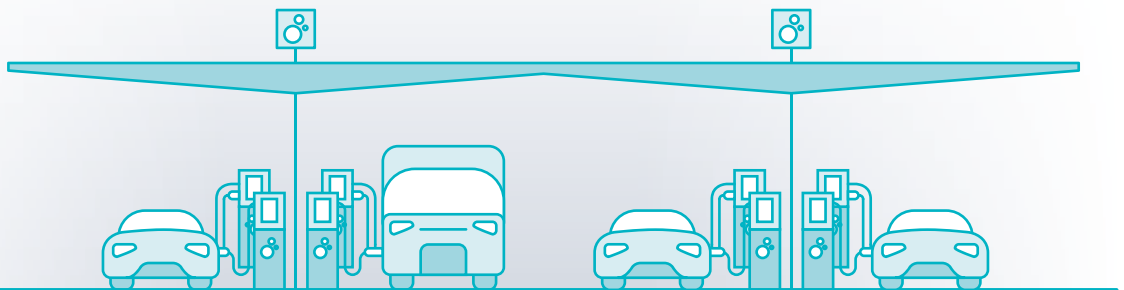
corresponding to approximately
28,000 to 32,000 additional
wind turbines (5 MW)

Alternatively, the option of producing hydrogen locally at filling stations was also considered. As is the case for the "100 % electric" scenario, periods of reduced electricity production from renewable energy sources must be bridged using reconversion in power-to-gas power plants. In return, the energy required for transporting hydrogen via truck, which comprises around 3 % of the transported energy content, is no longer an issue.

For the "100 % hydrogen" scenario, calculations from the wheel energy requirement result in a total primary energy requirement of between 502 TWh and 574 TWh when the hydrogen is produced centrally. This is equivalent to a factor of between 1.8 and 2 of the energy requirement in the "100 % electric" scenario. Decentralized production increases the primary energy requirement from 607 TWh to 703 TWh, which is mainly due to the requisite constant electricity supply and the associated losses during reconversion.

When observing the minimum fuel production costs, the difference between centralized hydrogen production in sunny regions (8 cents/kWh) and localized H₂ production at a filling station (18 cents/kWh) is quite significant. The route-related fuel costs for a fuel cell vehicle are therefore at least 32 % (car) and 42 % (truck) higher than the costs calculated for the "100 % electric" scenario. As the infrastructure for hydrogen filling stations does not yet exist, the 100 % scenario for hydrogen is based on assumptions for the desired network density. A minimum of 5,000 and a maximum of 10,000 filling stations (each with eight pumps) is seen to be sufficient for complete coverage. Based on the corresponding scale, the investment costs for each filling station have been estimated at 3.3 million euros.

Infrastructure requirement



H₂ filling stations

(each with eight pumps)

Minimum: 5,000

Maximum: 10,000

Costs of 3.3 million euros have been estimated for each filling station.

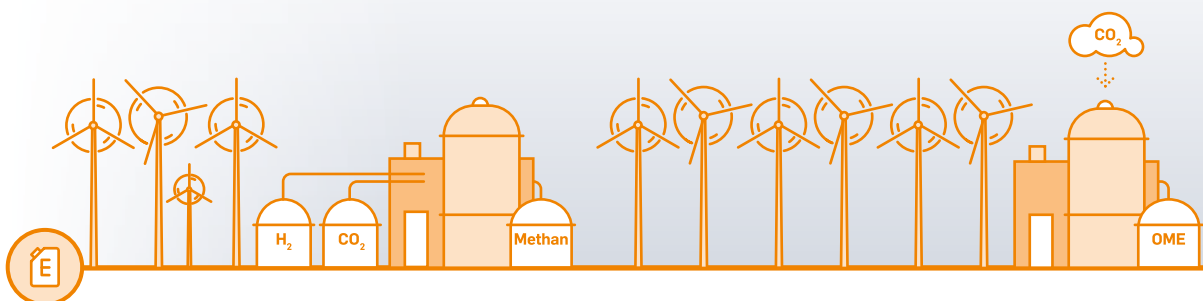
The "100% e-fuels" scenario

Closed material loops and the avoidance of waste form the basis of every ecologically responsible approach. The CO₂ produced when using fossil energy sources can also be regarded as waste which humanity disposes of in the atmosphere. In light of this, the idea was born to produce fuels based on water, carbon dioxide and regeneratively produced energy. These CO₂-neutral gaseous or liquid hydrocarbons do not require a fundamental conversion of the distribution infrastructure or vehicle propulsion technology due to their good storage and transport capabilities.

There are several alternatives for producing e-fuels, each of which differs considerably with regard to production processes and the chemical structure of the compound. As part of this study, a total of seven fuels in eight powertrain/fuel scenarios were in-

spected. The spectrum comprises two scenarios for methane, and one scenario each for methanol, DME (dimethyl ether), OME (oxymethylene ether), as well as synthetic gasoline, diesel and liquid petroleum gas based on the Fischer-Tropsch process. The

Total energy requirement



Minimum: 625 TWh (methane, CO₂ source available), corresponding to approx. 35,000 to 40,000 additional **wind turbines (5 MW)**

Maximum: 1,315 TWh (OME, CO₂ separation from air), corresponding to approx. 60,000 additional **wind turbines (5 MW)**

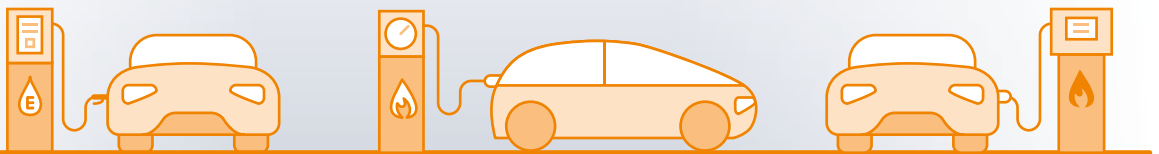
efficiency of the individual procedures is presented in a minimum and maximum observation using the expertise provided by the representatives from the energy and chemical industries. The provision of carbon dioxide has a significant impact on this, as the process of separating it from air requires additional energy. Assuming that anthropogenic CO₂ sources will continue to exist during the transition to a predominantly climate-neutral global economy, they can be used to produce e-fuels, at least in realistic mixed scenarios. In the best-case scenario, synthetic methane can be produced with a degree of efficiency of 65 %. The production of OME results in the worst degree of efficiency at just 31 % when coupled with CO₂ separation from air.

The energy conversion by a combustion engine is also a decisive factor for the total energy requirement and the potential here has not yet been completely exhausted. The degrees of efficiency used in this study are based on the best gasoline and diesel-powered cars from the compact vehicle segment available in 2015 (Volkswagen Golf, Ford Focus, Opel Astra). The option of converting combustion engine powertrains to electric drivetrains to signifi-

cantly increase efficiency was not considered. This method was chosen to better separate this scenario from the "100 % electric" scenario, although in reality electric and hybrid vehicle powertrains are expected to achieve very high market shares by 2030. Depending on the e-fuel and the combustion process, this observation results in an electrical energy requirement ranging from 625 TWh (methane, CO₂ source available) to 1,315 TWh (OME, CO₂ separation from air).

Although this study only observes paths to implementing climate-neutral road transport, the application area of e-fuels away from the road is also subject to intense discussions. Particularly for long-distance flights and deep sea shipping, alongside hydrogen, e-fuels are the only current option for achieving climate neutrality thanks to their high energy density.

Infrastructure requirement



The complete existing infrastructure can be used. Germany currently has:

- 14,000 filling stations for **liquid fuels**
- 6,800 filling stations for **liquefied petroleum gas (LPG)**
- 900 filling stations for **natural gas**

Comparison of costs and investment

From a current standpoint, it is probable that the costs for climate-neutral mobility will be higher than those for road transport powered by fossil fuels. From the standpoint of the users, however, the difference in mobility costs between the energy paths is not significant. The requirement for investment therefore fluctuates considerably, with additional vehicle costs dominating here.

When comparing the route-related costs, the minimum values for car traffic are between 28.4 euros and 33.1 euros per 100 km, as long as cost parity between electric and fuel cell vehicles and diesel vehicles is assumed. Under unfavorable framework conditions, the fluctuation is considerably higher at between 37.7 euros per 100 km and 52.8 euros per 100 km, with only decentralized hydrogen production at the filling station costing more than 50 euros per 100 km. The fluctuation range is greater for commercial vehicles. The route-related total mobility costs are between 70.1 and 155.2 euros per 100 km.

Each scenario presents different spans for the mobility costs:

- 100% electric: The actual mobility costs for users of a battery electric car can be between 29.4 and 45.1 euros per 100 km. For the study, the figures were calculated on the basis of a surcharge of between 2,400 and 11,300 euros for a battery electric powered mid-range car (with a range of 500 km) compared to a similar car with a combustion engine. The current VAT rate in Germany is taken into consideration. It is extremely difficult to predict the costs for electric vehicles in the future, meaning that predictions carry a relatively large degree of uncertainty. Mobility costs for trucks are

between 76.3 and 124.4 euros per 100 km.

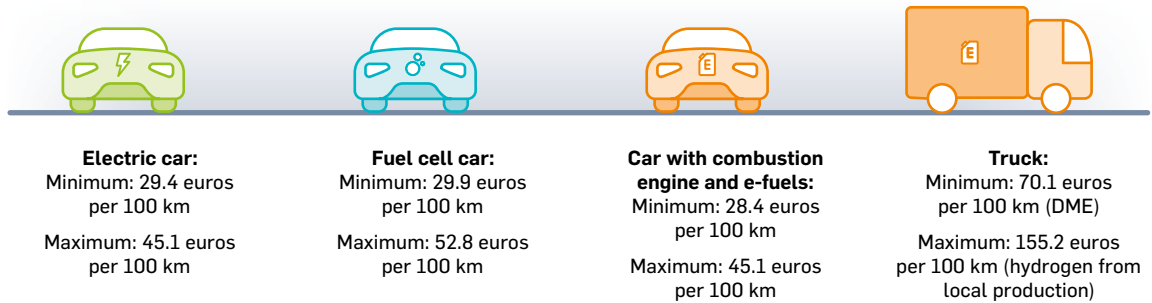
- 100% hydrogen: Taking into account the costs for energy provision, infrastructure and vehicles (surcharge of between 2,400 euros and 12,500 euros over cars with combustion engines), the mobility costs for a car are between 29.9 euros per 100 km (best-case) and 52.8 euros per 100 km (unfavorable conditions). This spectrum is also a result of the uncertain development of vehicle costs and location-dependent costs for hydrogen production.
- 100% e-fuels: Mobility costs range between 28.4 euros and 45.1 euros per 100 km when the CO₂ required for production is extracted from air. If other CO₂ sources can be used in a cost-neutral manner, the mobility costs are just 27.1 euros per 100 km in a best-case scenario.

It is to be assumed that the market acceptance of future propulsion concepts depends considerably on the complete costs. These costs are dominated by the vehicle costs (specifically their amortization) and not primarily the energy source costs. However, only the production costs of the energy sources are regarded and not potential taxes and fees. The infrastructure costs assigned to operators are comparatively low in all scenarios.

The scenarios do, however, display large differences regarding the total investment requirement, which amounts to between almost 300 billion euros and around 1,700 billion euros. Investments in the electricity generation capacity have a significant impact on this figure. The minimum investments in plants for fuel production and the distribution infrastructure only make up a small share here, fluctuating between 40 billion euros and 200 billion euros for the "100% electric" scenario. The cumulative additional costs for vehicles over 20 years have a greater impact. For the "100% electric" scenario, these are up to 860 billion euros, while the hydrogen scenario could cost up to approximately 980 billion euros. However, it must be pointed out that the costs for future vehicle propulsion systems over a long period (up to 2050) are subject to great uncertainty.

As such, the cumulative additional costs for cars could also be zero in the event of the appropriate technological progress. The investment risks for the hydrogen and electric scenarios are therefore significant. A further risk of the "100% electric" scenario is the expansion of the distribution networks, which in the least favorable case could cost up to 98 billion euros. The lowest risk with regard to fuel production and distribution is presented by the "100% e-fuel" scenario, as the maximum investments for all fuels are below 300 billion euros.

Mobility costs*



Investment requirement

	1 Investment costs for electricity generation	2 Investment costs for fuel production	3 Investment costs for infrastructure	4 Cumulative additional vehicle costs (20 years)
100% electric	€ 110 – 260 bn	0	€ 40 – 200 bn	€ 160 – 770 bn (car) € 50 – 90 bn (truck)
100% hydrogen	€ 90 – 340 bn (central) € 270 – 570 bn (local)	€ 70 – 90 bn (central) € 60 – 70 bn (local)	€ 20 – 40 bn (central) € 20 – 130 bn (local)	€ 160 – 850 bn (car) € 40 – 125 bn (truck)
100% e-fuels	€ 140 – 780 bn	€ 100 – 250 bn	€ 0 – 6 bn	€ 0 – 230 bn

* The mobility costs comprise the costs for the energy source (without taxes and fees), the costs for distribution and the amortization of the vehicle price (VAT included)

Climate protection and market acceptance

Future energy sources and vehicle propulsion systems should primarily be assessed based on their contribution to climate protection. Not only are the CO₂ emissions themselves to be observed here, but also the speed with which a high level of market penetration can be achieved, as only the total amount of greenhouse gases avoided by 2050 is relevant.

Market acceptance is not only dependent on mobility costs, but also on other criteria including the fulfillment of customer demands, such as those placed on the range. These are joined by social demands on local pollutant emissions, safety and the ecological compatibility of the required infrastructure expansion. The FVV study has therefore taken these questions into account for all three scenarios.

All three scenarios enable climate-neutral mobility in 2050 from a technical standpoint. However, this only applies for the “100 % e-fuel” scenario when the carbon required for production is taken from either biogenic CO₂ sources or is separated from the air. Two questions are therefore decisive for the time-dependent contribution to climate protection and must be answered for the respective technology path:

1. How quickly can the required infrastructure be installed for the respective path?
2. How quickly will the powertrain technology achieve sufficient acceptance among vehicle buyers?

In a market economy business model, the expansion of the infrastructure depends considerably on the willingness of individual companies to invest. The total investment for electricity generation, fuel production, infrastructure and additional vehicle costs calculated in this study total several hundred

billion euros and will probably not materialize without the state establishing an appropriate framework. This is particularly applicable to the “100 % e-fuel” scenario as it falls through the cracks in a “tank-to-wheel” observation, as is specified by the European Union for the CO₂ fleet emission targets. Locally, the engines powered by synthetic fuels emit carbon dioxide, even if it was separated from the air beforehand. The local CO₂ emissions related to the energy content of some e-fuels can even be higher than for fossil fuels, such as gasoline or diesel. Without allowances for the CO₂ avoided during fuel production, the industry sectors involved have no incentive to invest.




Regarding market acceptance, it should initially be pointed out that the vehicle purchase price and operating costs for the customer will continue to play a dominant role in the future. As described, the total costs do not differ greatly, particularly for cars, with each scenario enabling mobility costs of approximately 30 euros per 100 km. With regard to the powertrain costs (and therefore the vehicle costs), the “100 % electric” and “100 % hydrogen” scenarios still have a considerable range as the long-term cost reductions for batteries and fuel cells cannot be forecast with a sufficient degree of certainty. Furthermore, compatibility with the existing vehicle stock, i.e. the use of new energy sources

within the gasoline, diesel and gas infrastructure, can be useful for faster market penetration and thus a quicker reduction of CO₂ emissions from road traffic. This is generally the case for plug-in hybrid vehicles. Five of the observed e-fuels are suitable as admixtures for liquid and gaseous fuels used in road traffic today, even if only in limited amounts in some applications. Fuel cell vehicles are not compatible with the current infrastructure.

With regard to local pollutant emissions, only battery electric and fuel cell vehicles are completely emission-free. However, the target is to achieve “zero impact mobility” for all concepts. This also applies to future combustion engines with emissions which are so low they are almost impossible to measure and which will be far below the applicable legal limit values. Together with optimized engines,

e-fuels could potentially provide especially low raw emissions; however, further research is required in this area.

Unlike during the formative years of the automobile industry, it is no longer possible to introduce new technologies without a comprehensive risk assessment in the 21st century. The working group therefore examined all energy sources with regard to the risks in production, distribution and operation. The results showed that each technology path displays specific risks, however all paths are generally possible from a technical standpoint.

	Compatibility with existing stock (max. admixture in %)			
	Gasoline	Diesel	LPG	CNG
 Battery electric*	–	–	–	–
 Hydrogen	–	–	–	2
 E-fuels				
DME	–	–	–	–
OME	–	–	–	–
Methane – compressed (LD/HD)	–	–	–	100
Methane – liquid (HD)	–	–	–	–
Methanol (M100)	3	–	–	–
FT gasoline**	100	–	–	–
FT diesel**	–	100	–	–
FT propane**	–	–	100	–

* Electricity can be admixed indirectly as an energy source for plug-in hybrid vehicles. The share depends on the battery capacity in relation to the total range.

** Production procedure: Fischer-Tropsch (FT) synthesis

Outlook

The implementation of a 100 % scenario is neither desirable nor sensible. The FVV study provides facts required for political discussions, as well as identifying areas which require research in the future.

Several **fundamental conclusions** can be derived from the facts compiled in the study upon which this briefing paper is based:

- Implementing a “100 %” scenario is neither desirable nor sensible. The “100 % electric” reference scenario displays the lowest primary energy requirement, but will probably not be able to meet the requirements of all customers even in the future (charging time, range and vehicle costs). This is particularly applicable for cars traveling long distances and heavy commercial vehicles. It therefore seems expedient to follow at least one additional path, even when attempting to come as close as possible to fulfilling the “100 % electric” scenario.
- Realizing 100 % scenarios would probably be linked with the highest costs, which is why mixed scenarios are preferable from an economic point of view.
- In general, there are no technical hurdles preventing a combination of the “100 % electric” and “100 % e-fuels” scenario. The scenarios complement each other well, reduce the investment risks and together they could result in a faster reduction of traffic-induced CO₂ emissions. This applies in particular if e-fuels are not used as pure fuels, but as admixtures to fossil fuels during the transition period.
- Fuel cell powertrains harbor the potential to combine the advantages of battery electric vehicles (locally emission-free) and conventional cars (flexibility and suitability for long-distance

driving) in the medium and long term and at competitive costs.

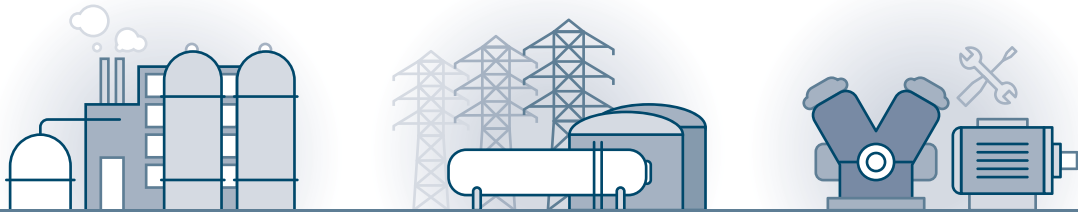
The required research can generally be split into the categories of “energy source” and “propulsion technology”, whereby they are closely interlinked regarding the climate goals and corresponding overall system observations are thus required.

There are two fundamental and influential research questions when it comes to the production of the respective energy sources. On the one hand, the efficiency level needs to be further improved in all process steps in order to reduce the total energy expenditure. An optimized efficiency level in this part of the energy chain not only means that less electricity generating capacity is required, but also increases the competitiveness of the German mechanical and plant engineering sector. On the other hand, the production processes – particularly for electricity as an energy source – and distribution systems will have to be able to handle different loads in an extremely flexible manner in the future. High flexibility and optimal efficiency represent conflicting goals, a factor which can however be reduced using cutting-edge technology.

Improving efficiency is and will remain a key area in propulsion technology. In this sector, the system efficiency in electrical drivetrains, as is examined in the FVV project “ICE2025+: Ultimate System Efficiency”, is particularly relevant. Furthermore,

the operating and long-term behavior of all power-train variants should be examined and optimized to meet the requirements of the vehicle owner. Examples include behavior at low temperatures and long-term stability. These factors are not just a challenge for traction batteries and fuel cells, but are also relevant for the e-fuels which have different chemical structures to fossil energy sources. It is also necessary to analyze the emission behavior of synthetic fuels on their own and when admixed to gasoline or diesel. Other e-fuels, such as gasoline synthesized from methanol, must also be examined with regard to their suitability for use in a vehicle.

Selected key research topics



Production of the energy sources	Energy provision	Vehicle and propulsion technology
<ul style="list-style-type: none"> • Highly dynamic electrolysis • Improving electrolysis efficiency, for example by using process heat • Highly dynamic hydrogen liquefaction • Storage requirement for renewable electricity and use in intermittently operated chemical plants • Hydrogen storage technologies (caverns, reconversion, etc.) • Costs and energy requirement for CO₂ separation from the air, as well as tapping of other CO₂ sources, such as from biomass. 	<ul style="list-style-type: none"> • Cost-reducing measures for H₂ pressure tanks • Infrastructure requirement and costs of the required electricity grid expansion including the installation of new plants for renewable energies. 	<ul style="list-style-type: none"> • Energy requirements taking into account real operating conditions, particularly at low temperatures • Customer acceptance • Required raw materials, technical availability and geopolitical dependencies (life cycle assessment) • Sub-zero emission potential and emission behavior under real operating conditions • Required modification of combustion engines to use e-fuels • Compatibility of e-fuels with fossil fuels and biofuels • Retrofitting capability • Operation with gaseous fuels in closed buildings • Suitability and costs of other e-fuels.

The briefing paper ›Energy paths for road transport in the future – Options for climate-neutral mobility in 2050‹ has been prepared for general guidance only. The reader should not act on any information provided in this paper without receiving specific professional advice. FVV does not guarantee the correctness, accuracy and completeness of the information and shall not be liable for any damage resulting from the use of information contained in this paper.

The content of this briefing paper is based on a detailed study by the FVV: ›Defossilizing the transportation sector – Options and requirements for Germany‹.

Both publications are available online:

→ www.fvv-net.de/en | Media

→ www.themis-wissen.de



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Road traffic is to be virtually climate-neutral by 2050.

However, this goal can only be achieved if renewable energies are used in the transport sector. A working group at the Research Association for Combustion Engines (FVV) has therefore analyzed various energy paths. The resulting study examines the use of electricity, hydrogen and synthetic e-fuels as energy sources in road transport, taking both technical and economic factors into consideration. This briefing paper summarizes the key results of the FVV study ›Defossilisierung des Transportsektors – Optionen und Voraussetzungen in Deutschland‹ (›Defossilizing the transportation sector – Options and requirements for Germany‹) (R586 | 2018) with the goal of enabling a fact-based dialog on future energy sources and propulsion concepts.

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