Fuel Cell and Battery Electric Vehicles

Significance for Electromobility

VDI/VDE study
June 2021

Foreword

Electromobility (electric transportation) undoubtedly represents an important contribution to climate protection and the use of renewable energy in the transportation sector. However, from the point of view of the VDI Society Energy and Environment (VDI-GEU) and the VDI Society Energy and Environment (VDI-FVT), as well as VDE's Energy Technology Society (VDE/ETG), the current discussion on the future of electric transportation in politics, the media, and the public lacks balance with respect to the characteristics of individual systems. The focus of the discussion tends to be primarily on battery vehicle applications.

The German government is currently supporting electric transportation via purchasing premiums and the development of a charging infrastructure. According to the coalition agreement, at least 100.000 additional charging points for electric vehicles were to be made available by 2020, and the construction of private charging stations to be promoted. With respect to hydrogen and fuel cells, the coalition agreement currently only provides for the promotion of so-called "sector coupling" and an adjustment of the regulatory framework for the introduction of "green hydrogen."

It is the opinion of the VDI-GEU, VDI-FVT, and VDE/ETG that fuel cell-based electric transportation can also make an important contribution to reducing greenhouse gas emissions. This assessment is shared by the railway operators and, in addition to cost aspects, a weighty reason for their decision to invest in fuel cell-driven trains, in addition to battery-operated ones.

A proper discussion also requires the consideration of all influencing factors. In addition to the specific interests of users, especially the economy with its special requirements and the strengthening of Germany as a business location, this also includes statements on the system's technical aspects. Likewise, the available raw materials must be evaluated and the ecological consequences taken into account. In this context, the technical and economic costs of producing and operating the new infrastructures must also be addressed.

VDI-GEU, VDI-FVT, and VDE/ETG have attempted to present the current state of development of fuel cell-electric vehicles (FCEVs) and battery-electric vehicles (BEVs) within the framework of an interdisciplinary working group from universities, research institutions, and industry. By involving a wide range of expertise, the relevant technical, ecological, and economic aspects of both technologies can be appropriately evaluated.

The analyses focus primarily on the passenger car sector; the truck sector is left out, despite its relevance to energy and climate policy, as are other options, such as synthetic fuels.

The aim of this study is to compare the advantages and disadvantages of these technologies as objectively as possible in order to provide representatives from politics, the media, and interested members of the public with the opportunity to obtain balanced information.

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Dipl.-Ing. Martin Pokojski
Chairman of the VDI/VDE Technical Committee
"Hydrogen and Fuel Cells"

Authors

The following persons from the working groups of the VDI-GEU and VDI-FVT, as well as VDE/ETG, collaborated in this study:

Frank Belmer, Shell New Energies, Hydrogen Operations Coordinator Europe, Hamburg

Dr.-Ing. Boris Bensmann, Gottfried Wilhelm Leibniz University of Hannover, Institute for Electrical Energy Systems (IfES)

Torsten Brandt, Siemens AG, Process Industries and Drives Division, Erlangen

Dr. Carsten Cremers, Fraunhofer Institute for Chemical Technology ICT, Pfinztal

Monika Derflinger, Ford Research & Innovation Center Aachen, Aachen, Germany

Prof. Richard Hanke-Rauschenbach, Gottfried Wilhelm Leibniz University of Hannover, Institute for Electrical Energy Systems (IfES)

Dr.-Ing. Thomas Grube, Institute for Electrochemical Process Engineering (IEK-3), Forschungszentrum Jülich GmbH, Jülich

Prof. Dr. Angelika Heinzel, ZBT GmbH - Centre for Fuel Cell Technology, Duisburg

Dipl.-Ing. Willi Horenkamp, Dortmund University of Technology, Institute for Energy Systems, Energy Efficiency and Energy Economics, Dortmund

Dipl.-Ing (FH) Thomas Jungmann, Fraunhofer Institute for Solar Energy Systems ISE, Department of Fuel Cell Systems, Freiburg

Stefan Kaimer, Ford Research & Innovation Center Aachen, Aachen, Germany

Paul Karzel, Shell Hydrogen Operations, Hamburg

Dr Martin Kleimaier, Essen

Dr Philipp Lettenmeier, Siemens AG, Hydrogen Solution, Erlangen

Dipl.-Ing. Martin Pokojski, Inecs GmbH, Berlin

Dr Gerd Sandstede, Frankfurt am Main

Dr. sc. ETH Zurich Michel Suermann, Gottfried Wilhelm Leibniz University of Hanover, Institute for Electrical Energy Systems (IfES)

Prof. Thomas von Unwerth, Faculty of Mechanical Engineering Chemnitz University of Technology, Chemnitz

Erik Wolf, Siemens AG, Hydrogen Solutions, Erlangen

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Abbreviations

AC	alternating current
BEV	battery-electric vehicle
CEP	clean Energy Partnership
CAPEX	capital expenditures
CGH2	compressed gaseous hydrogen (compressed hydrogen gas)
CNG	compressed natural gas
CO_2	carbon dioxide
DC	direct current
U.S. DOE	United States Department of Energy
EE	renewable energy
EEG	renewable Energies Act
EPA	Environmental Protection Agency
FCEV	fuel cell-electric vehicle
FCH-JU	Fuel Cells and Hydrogen Joint Undertaking
H_2	hydrogen
HEV	hybrid electric vehicles
ICE	internal combustion engine
ICT	information and communication technology
LCA	life-cycle assessment
LH_2	liquid hydrogen
LPG	liquified petroleum gas
MEA	membrane electrode assembly
METI	Ministry of Economy, Trade and Industry (Japan)
FMD	Mobility and Fuel Strategy
MSRP	manufacturer's suggested retail price
NFZ	commercial vehicles
PGM	platinum group metals

PHEV	plug-in hybrid electric vehicles
RED II	Renewable Energy Directive II
REEV	range-extended electric vehicles
SOC	state-of-charge (battery capacity)
TCO	total cost of ownership
TRL	technology readiness level (technology maturity level)
TWh	terrawatt hour
WACC	weighted average cost of capital
ZEV	zero emisssion vehicle

Core statements

Political objectives

- Fuel cell-electric vehicles (FCEVs) and battery-electric vehicles (BEV) are locally emission-free. In addition, they have the potential to support the political objectives of the German government with respect to reducing CO_2 emissions if renewable electricity is used to power them.
- Electric transportation promotes the use of renewable energy in transport and supports efforts towards sector-coupling.
- The production of fuel cells and fuel cell systems, including associated components, could enhance value creation in Germany.

Refueling and range

- Hydrogen enables rapid refueling with standardized refueling systems worldwide.
- The full refueling of an FCEVs is comparable to current internal combustion-driven vehicle refueling, at 3 min to 5 min. Even with the use of fast charging stations, the recharging of BEVs takes approx. 20 min, with a limitation of the charge to 80 % of their battery capacity (SOC).
- At the current state of development, FCEVs have a greater range compared to BEVs, and at the same time can transport larger payloads and provide their passengers with heating in winter without a significant reduction in range.
- BEVs currently use primary energy input more efficiently than fuel cell vehicles by at least a factor of 2. This does not take into account the storage effects of hydrogen and the potentially significantly lower intermittency of electricity sources offered by renewable energy technologies.

Infrastructure

- By using hydrogen produced on a large scale and expanding existing fueling station facilities, a rapid adaptation of the hydrogen infrastructure is possible. In the medium- to long-term, as with the charging infrastructure for BEVs, a gradual expansion of production and transport systems can be achieved.
- Due to the on-site storage of large quantities of hydrogen at fueling stations, demand peaks with the full utilization of the filling station will be unproblematic.
- With their low market penetration, infrastructure investments for BEVs will be lower. With a high market penetration, lower costs for H_2 infrastructure can be assumed, depending on the assumptions.
- H_2 transportation is usually affected by truck. In future, if there is greater demand, it will be possible to convert existing natural gas pipelines for exclusive H_2 transport.
- The provision of liquid hydrogen (LH_2) will lead to technically-simpler fueling stations, as the complex gas compression, pre-cooling, and quality analyses can be omitted. The amount of H_2 transported in a trailer can be increased to 4 t (a factor of 3 to factor 3,5 compared to pressurized gas transport).

Energy procurement

- Hydrogen procurement can generally be considered uncritical in terms of availability and costs (with a diesel equivalent price range) from market introduction to market ramp-up to mass market. Nevertheless, the supply of green hydrogen to fueling stations in Germany, both in sufficient quantities and at reasonable market prices, is currently associated with problems and therefore requires a further expansion of production capacity for green hydrogen.
- Hydrogen is becoming a global commodity. By sourcing it from countries with favorable electricity costs, H_2 procurement costs can be reduced.
- Hydrogen as a chemical energy carrier can be stored for longer periods without incurring losses. In conjunction with suitable storage systems (e.g., caverns), it is possible to decouple production and demand. This also includes seasonal storage and the creation of strategic reserves, comparable to today's fossil fuel storage practices.
- In the future, electrolysers and the use of an increasing renewable electricity supply from renewable sources should make it possible to largely produce hydrogen without emissions and in an economically-competitive manner.

- The use of electrolysers, as well as FCEVs and BEVs, offers the potential to optimize the power supply. By using these systems in a targeted manner, grid-serving operation is possible. Furthermore, waste heat from electrolysis can be integrated into heating systems and the oxygen can also be repurposed.
- Hydrogen can be used in different applications (e.g., electricity, heat, transport, and industrial processes). Hydrogen thus offers the potential for sector coupling desired by policymakers.

Critical raw materials

- Diversification of (electric transportation) technologies reduces the risk of raw material shortages.
- Critical raw materials include lithium, nickel and cobalt for batteries and platinum for fuel cells, with a declining trend. The production capacities of these materials must be expanded, preferably by increasing the recycling rate.

Costs

- The costs of using BEVs and FCEVs as passenger cars is currently predominated by acquisition costs.
- The series production of battery systems is more advanced than that of fuel cells. Accordingly, the cost reduction for battery systems is currently much more pronounced than for fuel cell systems.
- With higher energy or range requirements, FCEVs have cost advantages over BEVs. This effect increases with the start of series production.

Socio-economic factors

- Fuel cell vehicles contain some components that are comparable to those of conventional combustion engines, which can be adopted or adapted. This will open up new fields of business and create jobs.
- Fuel cell vehicles will continue to be hybridized with (small) batteries in the future. Developments in the battery sector will therefore also benefit FCEVs in terms of series production and costs.

Recommendations for action

Like battery technology, fuel cell technology can make a sustainable contribution to achieving the political goals in the transportation sector when renewable energy is used. The complementary technologies enable the substitution of conventional internal combustion-driven vehicles without compromising on comfort or practicality. In the medium to long term, they can contribute to reducing the economic costs of transportation compared to the current status quo. The prerequisite is the creation of the necessary framework conditions, which include:

- Expansion of the hydrogen infrastructure for public passenger and freight transportation: Public transportation is a key sector for the introduction of innovative transport systems, and currently makes a decisive contribution to air purity. The infrastructure will accelerate the market ramp-up in individual transport, as well as benefit the viability of electric vehicles.

- Realization of the planned 400 hydrogen fueling stations: The existing network of fueling stations is sufficient for some applications. However, from the private customer's point of view, the prerequisites for using hydrogen vehicles without restrictions can only be met when a sufficient infrastructure is in place.

- Review of regulations to speed up the realization of refueling stations: The deployment of hydrogen refueling stations is associated with various requirements that may delay implementation. In order to accelerate the approval process, uniform standardized procedures should be introduced throughout Germany while maintaining the high safety standards that have been developed. The need for approval according to the Federal Immission Control Act (BImSchG) when using electrolysers must be reviewed and reasonable exceptions defined.

- The inclusion of hydrogen as an energy carrier in the cross-sectoral long-term strategy for a secure energy supply: This contributes to planning security for the industry and attracts additional investment.

- Conversion to electric transportation: To support the market ramp-up, the conversion of vehicle fleets in both the private and public sectors is recommended.

- Accompanying research for the market ramp-up: Compared to conventional combustion engines, there is a need for research in the areas of ancillary systems, service life, and degradation behavior in real operation, as well as life cycle analyses for both batteries and fuel cells.

- Value creation in Germany: Today, a large share of value creation for batteries is not located in Europe; battery cell production predominantly takes place in Asia. In order to support competitiveness, policy should support the establishment of production facilities/workplaces for fuel cells and batteries in Germany by creating suitable framework conditions.

- Series production of components for electric drive systems: In the area of electric motors and batteries, manufacturing processes suitable for series production have been introduced. Further work is needed on fuel cells, components, and hydrogen storage systems, also to achieve the necessary cost reductions.

- The framework conditions for electric transportation: Non-discriminatory political framework conditions must be created. The eligibility, according to RED II (a requirement of the European Parliament), must be equal for both FCEVs and BEVs.

- Costs of energy procurement: The costs of electric transportation due to EEG levies, grid charges, and taxes must be reviewed.

Summary

Politics

The leading industrial nations support the introduction of electric transportation. For Europe in particular, the European Commission is pushing for the reduction of greenhouse gas emissions in the transportation sector via specific climate targets.

The German government supports electric transportation through purchasing premiums and the expansion of the charging infrastructure. With respect to hydrogen and fuel cells, the coalition agreement provides for the promotion of sector-coupling and an adjustment of the regulatory framework for the introduction of "green hydrogen".

FCEVs and BEVs can make equal contributions to supporting environmental policy goals when renewable energy is used. Fuel cell-electric drives also offer the potential to foster a high share of value creation for Germany and Europe more widely.

Refueling and range

The refueling characteristics and time of FCEVs is comparable to that of conventional petroleum- and natural gas-based vehicles. The refueling process is between 3 and 5 min and is comparable to a conventional vehicle running on liquid petroleum-based fuel. In comparison, the charging time for BEVs is up to several hours on a full charge, depending on the charging power. Using fast charging stations, a charging time (with a limit of 80 % of the battery capacity (SOC)) of approximately 20 min can be achieved.

The mechanical interface between the vehicle and dispenser, as well as the refueling process, are standardized worldwide for hydrogen refueling. In contrast, there are different plug-in systems and charging capacities for charging BEVs. Furthermore, the adaptation of the grid infrastructure is an essential prerequisite for the installation of DC fast-charging stations.

In BEVs, the performance of the battery correlates to its capacity. With increasing range, i.e., increasing capacity, the power and weight of the battery also increase. In contrast, with FCEVs, energy conversion and storage, and thus power and capacity, are decoupled. An increase in range, i.e., capacity, can be achieved by solely increasing the size of the tank. The increase in weight is small, which must be taken into account in the application to vehicles. BEVs today have advantages in the short-haul range, whereas FCEVs are highly advantageous in terms of payload and long-haul transport.

In conventional vehicles, the passenger compartment is heated by repurposing waste heat from the engine. In FCEVs, the waste heat from the fuel cell is generally sufficient for this purpose. In BEVs, by contrast, heating is only possible with the battery. This can significantly reduce the range at low ambient temperatures.

The conversion of the hydrogen in fuel cells into electrical energy is associated with efficiency losses. FCEVs are therefore significantly less efficient than BEVs. Compared to a vehicle with an internal combustion engine, however, an FCEV has a significantly higher efficiency, especially in the partial load range, which is the predominant operating range of passenger cars.

The energy balance of FCEVs can be improved depending on its use by additional batteries (plug-in). In this case, the battery is charged via both of the mains and during driving by the fuel cell or during the recuperation of braking energy, and therefore the advantages of both systems (BEVs and FCEVs) come into play.

Infrastructure

BEV and FCEV infrastructures are important building blocks for the transportation sector. They offer the possibility to achieve climate-friendly, clean, and renewable transportation concepts.

The advantage with respect to hydrogen is that it is easier to implement, as extant infrastructure can be used. Existing fueling stations can be expanded accordingly.

The refueling time of FCEVs is comparable to today's standard for petrol or diesel or LPG/CNG (liquid hydrogen/compressed natural gas). Accordingly, the capacity of hydrogen fueling stations is designed in a similar way to today's fueling stations. This means that many vehicles can refuel in succession at a fueling station within a certain period of time. By comparison, BEVs require a large number of charging stations to enable the simultaneous charging of a comparable number of vehicles during this period. This also applies to the use of DC fast-charging stations. Although these may shorten the charging times, the charging times are expected to be 3 to 5 times longer than for FCEVs with a limit of 80 % of the battery capacity. Therefore, a correspondingly larger number of parking spaces with charging facilities must be provided in order to achieve the same refueling capacity. This applies in particular to charging facilities along freeways. In addition, due to the fact that charging cannot be controlled in this case, an electricity grid expansion at the transmission grid levels may be necessary.

The space requirements of hydrogen dispensers do not significantly differ from those of today's petrol and diesel dispensers. Depending on the delivery concept, however, it can be assumed that more space is required for the necessary H_2 storage at the fueling stations.

As before, refueling is to be regarded as a separate process, and fueling stations must be accessible for this purpose. This may involve longer journeys, especially during the introduction phase of hydrogen fueling stations.

H_2 is usually transported by truck. In the future, if there is greater demand, it will be possible to use existing natural gas pipelines for H_2 transport by converting them.

Analyses of BEV user behavior has shown that BEVs are predominantly charged at users' homes and places of work. Nevertheless, solutions are also needed for BEV users without their own garage to enable recharging. These include public charging stations. So-called "lantern charging" is also currently under discussion.

In the case of overnight charging, a reduction in the expansion requirement for grid capacity can be assumed with controlled charging compared to the uncontrolled charging process. However, the implementation of this concept is highly dependent on parking spaces reserved for BEVs, as these must be equipped with charging facilities at varying degrees of expense.

Infrastructure investments for BEVs are lower than for FCEVs when the market penetration is low. With a higher market penetration, lower investments in H_2 infrastructure can be assumed. A mix of both systems – BEVs for shorter distances and FCEVs for longer ones – could result in a cost optimum being achieved. However, proving this requires detailed further investigation.

A scenario analysis by the Forschungszentrum Jülich and RWTH Aachen on the infrastructure requirements of BEVs and FCEVs reveals that, for large vehicle fleets of 20 million cars, the required investment in an H_2 supply system is lower than that for a battery charging infrastructure; the specific costs per kilometer driven, however, are comparable. The investment in the H_2 supply system takes into account not only the fueling stations and logistical components but also seasonal storage facilities equipped with a total capacity of 60 days' consumption. As a storage option for hydrogen, salt caverns are an especially cost-effective means of storing large quantities (several 10 TWh) of renewable energy. The necessary investment for charging BEVs includes the costs of charging stations and expansion requirements for distribution grids. Any necessary grid expansion in the transmission grid and seasonal storage has not yet been taken into account. However, a comparison should also take into account the cost of long-term storage for renewable energy for BEVs.

Energy procurement

In every phase of market introduction, the procurement of hydrogen is not critical in terms of availability and costs. While in the short term, by-product hydrogen from industrial processes and from methane steam reforming can be made available, in the medium to long terms, only renewable primary energy should be used for H_2 production.

Hydrogen is becoming a global commodity. Studies on global H_2 logistics also show that it can be produced cost-effectively in regions at an especially high volume using renewable power and transported to center of consumption by ship, for example.

Taking into account the necessary infrastructure components, it can be shown that H_2 costs at the filling station are competitive with today's fuel costs (in each case, excluding taxes and duties). By comparison to battery vehicles, however, it must be taken into account that the electricity price for battery vehicles includes taxes and duties, which places them at a disadvantage compared to hydrogen-powered vehicles.

Hydrogen as a chemical energy carrier can be stored cost-effectively for longer periods without losses but undergoes higher conversion losses. In combination with suitable storage systems (e.g., caverns), it is possible to decouple generation and demand up to seasonal storage.

Hydrogen offers the possibility of being used in different sectors (e.g., electricity, heat, transport, and industry). The energy carrier thus offers the potential for sector-coupling desired by policymakers.

The use of electrolysers for hydrogen production would enable an emission-free energy supply, provided that they are operated with electricity from renewable energy sources. However, their economically-competitive use requires favorable electricity prices.

Electrolysers for supplying FCEVs and BEVs offer the potential to optimize the power supply. By employing these systems in a targeted manner, grid-serving operation is possible.

Critical raw materials

In the field of electric transportation, lithium, nickel, and cobalt for batteries and platinum for fuel cells, as well as rare earth metals for electric motors, are considered the critical raw materials.

In order to avoid raw material shortages or price increases, the production capacities of all of the critical raw materials mentioned must be increased, especially those for lithium and cobalt. At best, this will be realized by an increased recycling rate, which does not yet exist on a technical scale, especially for lithium.

Increased recycling would also reduce the risk of structural shortages in particular, which can occur with secondary metals, as their mine production volume only depends on the primary metal. This applies, above all, to cobalt and, to some extent, platinum. In the same way, monopoly-like structures in the areas of “mining production” and “raw material reserves”, such as exist for rare earth metals (China), platinum (South Africa), and cobalt (Congo), would be mitigated and broken up in the long term.

As things stand today, only the raw material reserves of cobalt and nickel would not be sufficient, if at all, for the predicted electric transportation through 2050 and including all other applications, but their raw material resources would be. Therefore, price increases and temporary shortages are fairly conceivable unless corresponding new mining the same extent. Absolute shortages, on the other hand, are somewhat unlikely, as usually either new raw material deposits are sighted and developed beforehand or raw material substitutions are initiated. There have already been successful initial developments in the much more efficient use of these critical raw materials, or even their full substitution.

Costs

The costs for the use of BEVs and FCEVs are currently predominated by acquisition costs. As cost reduction through series production is more advanced for battery systems than for fuel cell ones, FCEVs are currently at an economic disadvantage due to their later market introduction.

With the start of series production for fuel cell systems, the cost advantages of FCEVs can be expected for vehicles with higher energy or range requirements at the time of purchase. Larger FCEV vehicles, such as SUVs, may initially have cost advantages, as comparable BEVs require correspondingly large batteries. For smaller vehicles, a somewhat later cost parity can be assumed.

Open questions

The analyses within the framework of this study show that there is insufficient information on various points, or that the available information is partly inconsistent. This suggests the need for further research. In particular, this affects the topic blocks, “Ancillary systems,” “Life cycle analyses,” “Service life of the systems,” and “Series production processes for their components.”

1 Introduction

The reduction in greenhouse gas emissions is the primary goal of global climate policy. Fossil fuels must be replaced by renewable sources in all economic sectors. In the transport sector, electric drivetrains are one important solution. They are characterized by very high efficiencies compared to internal combustion engines and enable the use of electricity generated from wind energy and photovoltaics. This is of great importance, because the share of biogenic energy sources is limited, and the agricultural land required for this is in competition with food production. Furthermore, in the case of road transport, the local absence of emissions from electric drivetrains is of great significance and represents the only way to sustainably reduce local emissions – including noise – and significantly improve quality of life in urban centers.

The term “electric transportation” essentially includes all vehicle systems that use electric drive systems. They are available in various technical forms. In addition to the currently intensively-discussed battery-powered vehicles, especially those that utilize lithium-ion batteries, this also includes systems that use hydrogen as an energy carrier. Hydrogen can be produced by means of electrolysis – preferably powered by renewable electricity – and converted back into electrical energy by means of fuel cells (typically low-temperature polymer electrolyte fuel cells, or PEMFCs) on board the vehicles. In contrast to battery vehicles, where electrical energy is stored in batteries, in the fuel cell vehicles of today, the hydrogen is usually stored in pressure vessels at high pressure. This technology has prevailed over previously envisaged storage systems with cryogenic liquid hydrogen or methanol-based systems with H_2 reformers.

In parallel to electric vehicles, the oil and motor vehicle industry is working on systems that use synthetic fuels – liquid or gaseous – as energy sources for combustion engines. These serve as a substitute for fossil products, and are obtained via regeneratively-produced hydrogen, as well as carbon dioxide, e.g., from the air, biogenic sources, or industrial processes. As the amount of carbon dioxide released during on-board combustion is precisely the amount required for production, these fuels are considered climate-neutral. An advantage here is that the widely discussed range problem, especially with respect to battery systems, would no longer be an issue due to energy density, which is comparable to that of today’s vehicle fuels. The disadvantage, however, is the lower efficiency of the entire chain due to the additional conversion losses entailed during the production of these fuels, as well as the poorer efficiency of the combustion engines. Furthermore, local emissions remain and the production plants for synthetic fuels require large investments, as they encompass CO_2 provision, hydrogen production, and product synthesis.

The topic of climate-neutral transportation will play an important role (in the near future) in air, rail, ship, and road transport. Road transport includes passenger cars and trucks, buses, bicycles and, in a broader sense, industrial trucks and forklifts.

The following explanations focus on battery-electric and fuel cell-driven vehicles. The aim is to show what outcomes can result from the use of the different technologies. The advantages and disadvantages of the individual developments are presented in accordance with the current state of knowledge.

In addition to the already mentioned possibility of being able to use renewable energy, it is relevant that electrolysers in particular, with which hydrogen is produced from renewable electricity, are suitable for comprehensive system integration. In addition to the use of electricity and gas grids to transport electrical energy and hydrogen, this also includes measures enabling more flexible energy supply and demand by using electrolysers. It also offers the possibility of providing heat, which is a by-product of electrolysis, when there is local demand.

2 Market development of fuel cell vehicles

H_2 as an energy carrier and fuel cells as energy converters for the transportation sector have been investigated, evaluated, and deployed in numerous projects. It has been recognized that H_2 fuel cell solutions could achieve significant market shares by 2050 [1]. This is due to the easy handling of H_2-powered vehicles, their long range, and the fulfilment of technical challenges.

2.1 Application potential

There is a large market for electrically-powered vehicles. For example, logistics companies are already operating electric or gas-powered forklift trucks in shift patterns. In order to further increase utilization in this setting, fuel cell-powered forklifts that can be refueled very quickly are already being used today. The largest market share of fuel cell-powered vehicles is expected to be around 65 % for forklift trucks in 2050 [1]. Fuel cell forklifts are already considered to be technically mature, at TRL 9, and suitable for the mass market [1]. In the USA alone, more than 16.000 [2] fuel cell forklifts have been procured or ordered since 2009, and have been successfully used commercially by a wide range of end customers [3; 4]. Compared to battery-powered forklifts, there are clear advantages due to the longer service life of fuel cell stacks, the longer range it affords, the significantly faster refueling times and lower operating costs [5]. In addition, fuel cell forklifts are also highly promising due to their unproblematic and safe handling [5].

Fuel cell cars (FCEVs) have also reached full technical maturity [6], which is confirmed by practical experience: As early as 2011, three B-Class F-Cell models from Mercedes Benz successfully covered 30.000 km in 125 days around the world as part of the F-Cell World Drive [7, 8]. In the meantime, FCEVs from Honda, Toyota, and Hyundai are also commercially-available [6]

Compared to fuel cell cars, fuel cell buses are expected to have a higher market share in the future. Moreover, they stand at TRL 8, meaning that almost complete technical maturity has been attained [6]. In real-world operation, fuel cell buses have already achieved the U.S. Department of Energy (DOE) targets of 20.000 driving hours [9]or 25.000 driving hours [10]and numerous projects have reached a positive conclusion: “All of these projects have proven that fuel cell buses can operate with the same flexibility as diesel buses without compromising the productivity of public transport” [11]. A significant reduction in acquisition costs has also been recorded in recent years [12; 13].

Due to the numerous use cases, it is not surprising that the importance of fuel cell technology has been growing significantly, especially in the transportation sector in North America and Asia [14]. These growth rates will also lead to an increase in the number of people employed in the fuel cell sector.

2.2 Sales development

In recent years, there has been a strong growth in sales for all electric transportation variants (Figure 1). These currently account for about 1 % of the global market [15]. Comparatively speaking, new BEV passenger car registrations, at a good 750.000 vehicles in 2017 alone, are higher than PHEVs and FCEVs by a factor of 2 and 230, respectively. The largest current sales market is the People’s Republic of China, where every second BEV is already being sold.

The large sales discrepancy in the area of zero emission vehicles (ZEVs) is due to the earlier (mass) market entry of pure battery vehicles compared to fuel cell vehicles, significantly more vehicle models, and a tendency towards a better degree of expansion of the charging infrastructure. Nevertheless, new FCEV registrations have also expanded rapidly in the three current sales markets of the USA (California), Japan, and Europe (Figure 1).

From the consumer’s point of view, acquisition costs play a decisive role. With respect to the market developments of BEVs, PHEVs, and FCEVs, the fact that battery vehicles can be built smaller and cheaper comes into play. The falling costs of Li-ion batteries support this; at under €200/kWh, they are now approaching the cost of raw materials. Contributing to these cost reductions has been the efforts of various manufacturers (Tesla, Samsung, LG, etc.), who are bringing battery cells for electric vehicles to market.

As far as the current price situation for ZEVs is concerned, Table 1 shows indicators for the three main markets of Germany, the USA, and Japan. In the USA, for example, the Toyota Mirai is listed at $58.365 (USD), with a range of just under 620 km and the Tesla Model S (75 kWh) with a range of 490 km at a price of $74.500 (manufacturers’ non-binding prices). This corresponds to a purchase price saving of around $16.000 or 160.000 km driving distance (at $10/kg$H_2$), roughly comparable to a typical car lifetime.

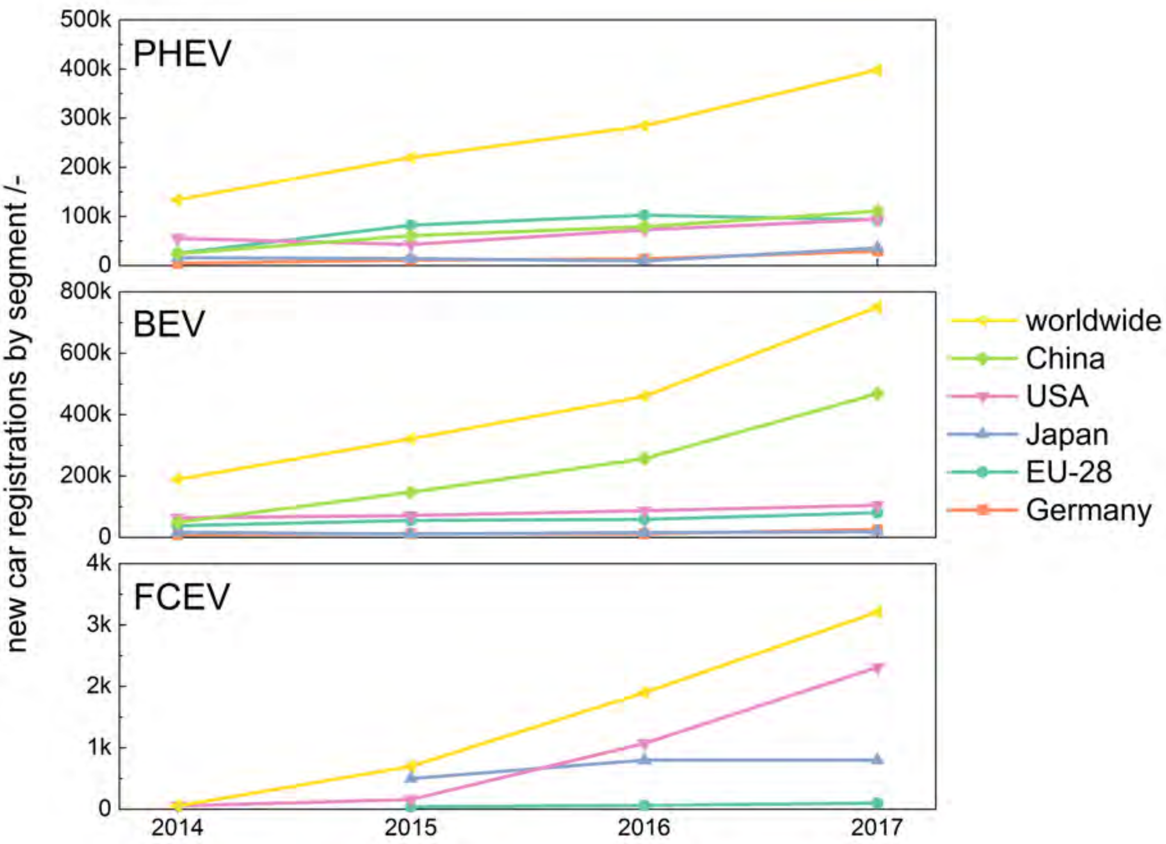

Figure 1. New BEV, FCEV and PHEV registrations from 2014 to 2017 [16; 17]. (Source: University of Hanover)

Table 1. Current list prices for three representative ZEVs [18] (source: Fraunhofer ISE)

	Germany	USA		Japan	
	€	USD	€	Jap. yen	€
Toyota Mirai	78.600	MSRP of 58.365 (+ 895 for delivery)	48.923 (49.652)	7.236.000	55.500
Tesla Model S75	69.999 (71.999 without eco-rebate)	74.500	62.319	9.600.000	73.632
Nissan Leaf 40 kWh (ZE1 equipment)	31.950	29.900 (22.490 after federal tax credit)	25.136 (18.850)	3.150.360	24.195

3 Evaluation criteria of electric transportation technologies

An objective evaluation of the technologies discussed here requires the recording of all essential influencing variables. In addition to the political objectives and the strengthening of Germany as a business location, these include market development, technical aspects, questions regarding infrastructure, possibilities for emission-free transportation, the availability of raw materials, lifecycle cost analyses and customer benefits. This study is therefore based on the evaluation criteria listed in Figure 2. These are explained in Section 4 and evaluated in as much detail as possible.

Political objectives

Technical advantages

Refuelling

Driving range

Efficiency

Infrastructure

Energy procurement

Emission-free mobility

Critical raw materials

Life Cycle Cost

Value creation

Customer benefits

Figure 2. Evaluation criteria for electric transportation

On the basis of these criteria, the following further criteria were defined for the categories:

- political objectives
- refueling and range
- infrastructure
- energy procurement
- critical raw materials
- costs (TCO)

Taking into account customer benefits, core statements were developed that are elaborated in more detail in the following sections.

4 Electric transportation – Key statements and arguments

4.1 Political objectives

Core statements

- FCEVs and BEVs are locally emission-free. In addition, they have the potential to support the political objectives of the German government with respect to reducing CO_2 emissions if renewable electricity is used to power them.
- Electric transportation promotes the use of renewable energies in transport and supports efforts towards sector coupling.
- The production of fuel cells and fuel cell systems, including associated components, could enhance value creation in Germany.

Ecology/emission-free transportation

The introduction of electric transportation is supported by the leading industrial nations. Policymakers are pushing this process by designing appropriate framework conditions.

The European Commission's climate targets support the reduction of greenhouse gas emissions in the transportation sector. The Environment and Energy Plan, which the Commission presented in 2014, envisages a 40 % reduction in greenhouse gas emissions by 2030 (based on 1990 levels). The share of renewable energy is to be increased by 27 % by then, and an improvement in energy efficiency (e.g., a reduction of thermal losses), also by 27 %, is set to be achieved [19].

Specifically for the transport sector, the EU promotes the introduction of innovative propulsion systems in its White Paper and corresponding directives:

- The White Paper on Transport [20] assumes that the share of conventional vehicles in urban logistics can be halved by means of electric transportation. By 2030, it should be possible to achieve CO_2-free urban logistics.
- Regulation 333/2014 [21] requires a reduction of the average CO_2 emissions of new car fleets to 95 g of CO_2 per km by 2021. This corresponds to a petrol consumption of about four liters per 100 km.
- Directive 2014/94, "Alternative Fuels Infrastructure" [22], provides for the increased dissemination of environmentally-friendly alternative fuels. For partially and fully electric vehicles, the infrastructure must be expanded with non-discriminatory access to public charging infrastructure.

These targets are reflected in the different activities of the EU member states. Among others, the UK [23] and France [24] have announced a ban on the sale of fossil fuel vehicles by 2040. The Swedish car manufacturer Volvo plans to produce and offer only hybrid or electric cars from 2019 [111]. VW also announced in December 2018 that it would commence its final production series of internal combustion engine-based vehicles in 2026 [112].

For Germany in particular, the Federal Government conceives electric transportation as making a contribution to uniting technological progress and environmental/climate protection. It offers the opportunity to strengthen the leading position of German companies in the global market and to support economic development in Germany. In this manner, large-scale driving bans in cities could be avoided [25]. It therefore supports the introduction of electric transportation with, among other things, purchase premiums for the acquisition of electric vehicles, with the concomitant promotion of the expansion of a charging infrastructure and the procurement of electric vehicles for the public sector [26].

Relevant statements in the coalition agreement of the new German government [27] support this. According to these, the government is committed to the Paris Climate Agreement and the German Climate Protection Plan 2050 with its transportation policy. With respect to hydrogen and fuel cells, the National Innovation Programme and the Mobility/Fuel Strategy (FMD) are to be further developed in a technology-open manner and the funds for their implementation are to be increased. Sector coupling is to be advanced and the regulatory framework changed so that "green hydrogen" and hydrogen as a by-product of industrial processes can be used as a fuel or for the production of conventional fuels (e.g., natural gas/CH_4).

With respect to electric transportation (battery-electric and hydrogen fuel cell), existing funding programs are to be increased and supplemented beyond 2020 where necessary. The development of a nationwide charging and refueling infrastructure is also to be intensified. By 2020, at least 100.000 additional charging points for electric vehicles should be available, at least one third of which should be DC fast charging points. For the sustainable conversion of bus fleets to alternative drivetrains, suitable charging infrastructures and operational management systems are planned, in addition to the vehicles. With respect to hydrogen, in 2016 the Federal Government already adopted the second government program on hydrogen and fuel cell technology for 2016–2026. This program forms part of the Federal Government's innovation strategy and is a building block for a sustainable energy system [29].

A look at other regions confirms the global interest in electric transportation:

- In **Europe**, the activities of the French government are worth noting [29]. France's hydrogen development plan is intended to enable the industry to play a leading role in the global industry. Up to 5.000 H_2 vehicles are to be put on the road by 2023 (currently there are 250). For the H_2 supply of these, the establishment of 100 fueling stations is planned, expanding the present 20. The target market for H_2 application is primarily the commercial sector, the aim being to use hydrogen in taxis, construction machinery, city buses, coaches, trucks, and railways.

- **China** in particular is striving for the rapid electrification of its transportation sector. The country already had 500.000 electric vehicles and plug-in hybrids in 2016 [30]. By 2025, the Chinese government aims to have increased the share of e-vehicles to 7 million. According to BYD CEO Wang Chuanfu, China aims to fully electrify transportation in the country by 2030. Public buses could be fully electrified by 2020, trucks and special vehicles by 2025. The current lack of batteries could prove to be a problem, however, with experts expecting a bottleneck by 2020.

- Japan announced at the 2015 World Climate Conference in Paris that it would aim for a 20 % to 30 % market share for electric cars and plug-in hybrids by 2030.

  One focus of Japan's activities has been the introduction of hydrogen propulsion. Japan supported efforts to promote hydrogen as an energy carrier at an early stage. Among other things, the Tokyo Metropolitan Government (TMG) aims to promote the construction of fueling stations and other H_2 infrastructural elements by 2020, the originally intended year of the Olympic Games, with an investment volume of $348 million (USD) [31].

  From the point of view of the Japanese Ministry of Economy, Trade, and Industry (METI), buyers have three reservations about electric cars: their high price, short range and the low number of charging stations. This is where government support will come in. The high price will be reduced by partially or fully waiving taxes on electric cars. Subsidies will also reduce the purchasing price by an average of 5 %.

  In order to increase the range, car manufacturers are being encouraged to develop more powerful batteries. The state supports this by increasing the subsidy for the purchasing price within the range. For each kilometer of range, the state will pay 1.000 yen (€7,40 EUR).

  In terms of charging infrastructure, the government is funding the construction of charging stations with over 55 billion yen (€407 million). The regional prefectures are also contributing funds to this. By the end of March 2017, around 40.000 charging stations were already available [32]. In addition, the city government of the capital of Tokyo intends to subsidize the construction of charging stations for flat blocks and high-rise buildings starting this year.

- **USA**: Although the administration of President Donald Trump was skeptical of climate change and allowed higher CO_2 and nitrogen oxide emissions for new US cars between 2022 and 2025 [33], dozens of US cities are in favor of reducing greenhouse gas emissions and the addition of greater climate protection measures.

  30 US cities, including New York City and Chicago, plan to purchase a total of 114.000 electric vehicles worth $10 billion USD for urban use in the coming years. These include police vehicles, street sweepers, and garbage trucks. The number of orders corresponds to about three quarters of the total electric car sales in the USA last year.

  According to Los Angeles' environmental commissioner, cities will continue to lead the way in addressing climate change, regardless of decisions made by the US Federal Government. Los Angeles began requesting electric cars in conjunction with three other cities in late 2015. The initial request was for 24.000 electric cars, but 26 other cities have since joined.

  Further support for electric transportation has come from a campaign by 16 car manufacturers and seven US states [34]. They are investing $1,5 million in ads such as "Drive Change, Drive Electric," which highlight the benefits of electric cars. The carmakers include Daimler-Benz, BMW, Volkswagen, Toyota, and General Motors, and the states include Connecticut, Massachusetts, and New York. Despite high investment by the carmakers, however, sales have been fairly low so far.

Value creation

In the automotive industry, Germany is characterized by extremely high vertical integration and a complete value chain. This situation could change profoundly with the growing use of BEVs, as currently, battery production is primarily conducted in the USA and certain Asian countries.

Germany also has excellent competencies in the field of electro-technical components. The situation is open when it comes to the production of fuel cells though. Here, the automotive industry has long relied on Canadian know-how, but has always pushed ahead with parallel developments. In North America and Japan, manufacturers of fuel cell stacks have already been able to establish themselves, and in Germany, "Autostack Industrie," a project to prepare for mass production, is being promoted within the framework of the NIP (with Daimler-Benz, VW, Ford, and other partners).

Fuel cell-electric drivetrains essentially comprise the assemblies electric drivetrains, with an electrical motor, power electronics, buffer battery, power generation with the fuel cell stack, peripheral components for the anode supply (hydrogen), cathode supply (air), cooling, and power feed into the vehicle intermediate circuit, as well as hydrogen storage, including safety and refueling devices.

Each of these assemblies, in turn, comprises a large number of components, some of which require special materials for their production, meaning that a structured value chain can be built up that is analogous to that for today's drivetrain technology. There are already a number of companies active in this area in Germany and Europe more widely, particularly material and component suppliers. In Europe, for example, this is shown by the overview of the value chain for fuel cell systems as researched by the Fuel Cell and Hydrogen Joint Undertaking [35]. In their survey, almost 50 companies stated that they are active in the field of fuel cell vehicles other than fuel cell buses, of which about 15 are vehicle integrators. In the area of fuel cell buses, there are even more market participants, with a total of more than 80 active companies, of which more than 30 describe themselves as vehicle integrators.

The Fuel Cell Industry Guide Germany 2018, published by the Fuel Cell Working Group in the VDMA [36], lists a total of 57 active companies and institutions in the field of fuel cells, regardless of application. According to the results of an industry survey listed there, these companies achieved a turnover of 190 million EUR in Germany in 2017.

Germany and Europe are especially strong in the field of components and materials. For example, one of the leading companies for electrocatalysts has its headquarters in Europe, and two other important manufacturers are located in Germany. Likewise, one of the world's leading manufacturers of electrolyte membranes is based in Europe. There are also several manufacturers of membrane electrode units throughout Europe, one of which is in Germany. The same applies to bipolar plates and sealing technology. In recent years, a number of suppliers of fuel cell stacks for automotive propulsion have also established themselves in Europe. The Autostack and Auto-Stack Core activities of the Fuel Cells and Hydrogen Joint Undertaking (FCH-JU), which are currently being continued within the framework of the "Autostack Industry" project, financed by the Federal Ministry for Economic Affairs and Energy, were certainly decisive here. The industry is also strongly represented in the area of tank and high-pressure technology.

Overall, fuel cell-electric drivetrains offer the potential for Germany and Europe to contribute a high share of value creation, with corresponding effects on the labor market, for instance. Currently, there are no known parts or components for which a market-dominating position by non-European companies has already been established. However, global production capacity remains very limited, as there are no alternative sales markets for most fuel cell components, in contrast to batteries, for which cells are also produced on a large scale for the Information and Communication Technology (ICT) and consumer markets, for example.

4.2 Refueling and range

Core statements

- Hydrogen enables rapid refueling with standardized refueling systems worldwide.
- The full refueling of an FCEVs is comparable to current internal combustion-driven vehicle refueling, at 3 min to 5 min. Even with the use of fast charging stations, the recharging of BEVs takes approx. 20 min, with a limitation of the charge to 80 % of their battery capacity (SOC).
- At the current state of development, FCEVs have a greater range compared to BEVs, and at the same time can transport larger payloads and provide their passengers with heating in winter without a significant reduction in range.
- BEVs currently use primary energy input more efficiently than fuel cell vehicles by at least a factor of 2. This does not take into account the storage effects of hydrogen and the potentially significantly lower intermittency of electricity sources offered by renewable energy technologies

The basic structure of BEVs and FCEVs is displayed in Figure 3. As can be seen from the illustration, fuel cell vehicles also utilize batteries, albeit with a significantly smaller capacity. Among other things, they enable the recovery of braking energy [37].

For a decision in favor of one of the two systems, the charging process, range, efficiency of the entire energy chain, durability, and operability in extreme conditions (e.g., frost, heat) are relevant, in addition to the acquisition costs. For an overall assessment, the cost of the required infrastructure and a lifecycle assessment are also important.

Hydrogen refueling is more compatible with current refueling habits compared to battery charging infrastructure

In terms of the refueling or charging process, FCEVs and BEVs exhibit clear differences:

- The refueling process of FCEV passenger cars is completed within 3 min to 5 min, and for commercial vehicles approx. 10 min is to be estimated. Compared to the refueling process for fossil fuel-based vehicles, there are only minimal differences (Figure 4) [38].
- Compared to H_2 refueling, the charging times for BEVs are expected to be 3 to 5 times longer, even with fast charging capacities at battery charging facilities. Therefore, a larger number of parking spaces with charging facilities must be provided at each charging location in order to be able to achieve the same refueling capacity. In addition, due to the fact that charging cannot be controlled in this case and the high connection power required, a network expansion may be necessary.
- In the case of overnight charging, controlled charging can be assumed to reduce the need for the expansion of grid capacity. In this case, integration is highly dependent on parking spaces that can be reserved for battery vehicles, as these must be equipped with different levels of charging facilities.

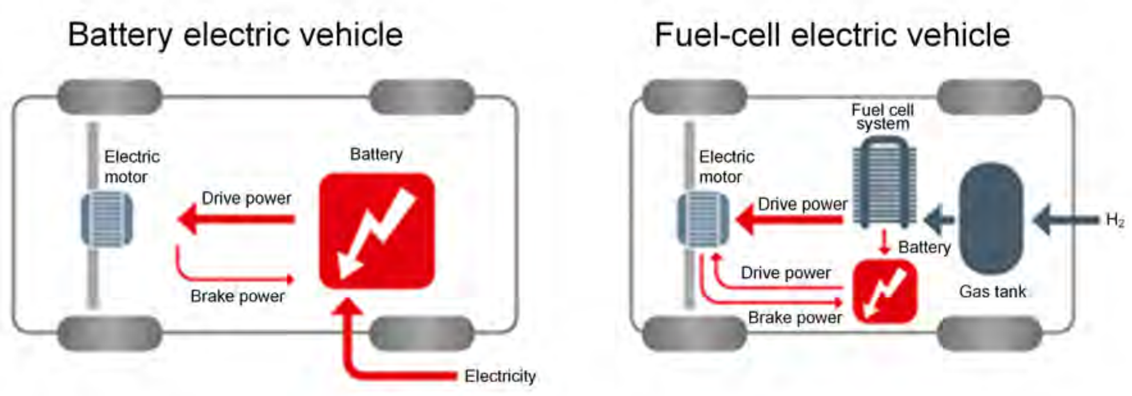

Figure 3. Principles of BEVs and FCEVs (source: Jülich Research Centre)

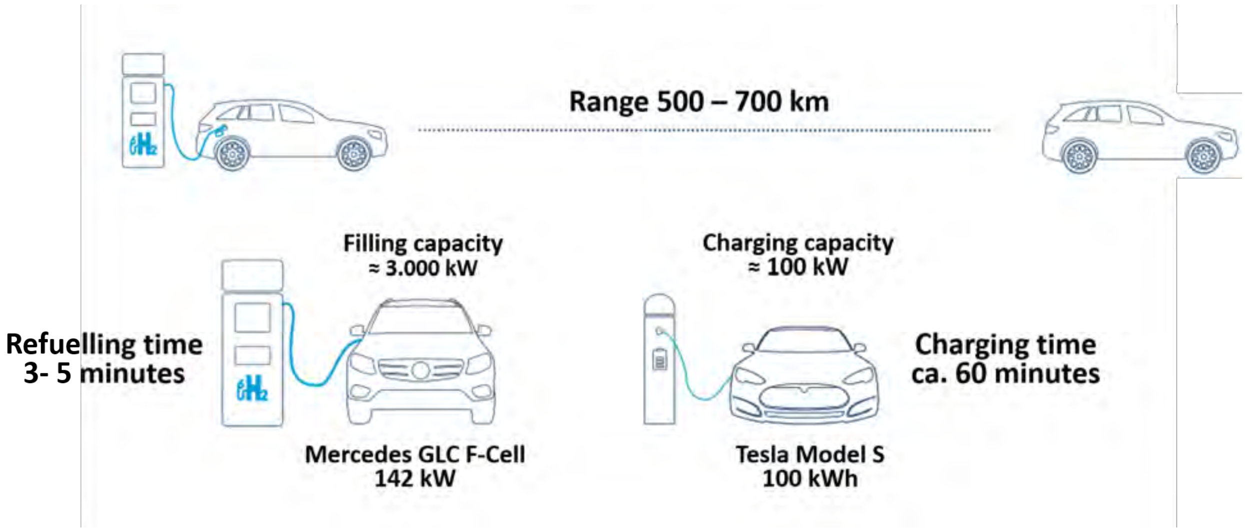

Figure 4. H_2 refueling and the charging of electric vehicles (source: H2Mobility)

Figure 5. H_2 refueling (source: H2Mobility)

FCEVs

The refueling characteristics of FCEVs are comparable to those of conventional vehicles. The refueling process takes place with the help of special dispensing devices, which are similar to petrol or diesel refueling systems (see Figure 5) [38]

Fueling station concepts for FCEVs assume that hydrogen is stored at pressures of 900 bar to 1.000 bar; a storage pressure of approximately 700 bar is envisaged for the vehicles themselves. The required fueling devices (dispensers, Figure 5) have shown their suitability for everyday use in the context of larger demonstration projects, including the HyFLEET:CUTE project of the European Commission [40] and the Clean Energy Partnership (CEP) [41]. It must be taken into account that during refueling, a smaller part of the gas (the gas volume in the tank tube) is discharged after the refueling process has been completed. This loss depends on the respective design of the dispenser and typically amounts to 7 g to 10 g, i.e., around 0,3 kWh (0,07 %).

H_2 storage on board the vehicles is usually in gaseous form (CH_2); in cars at a pressure of 700 bar, and in trains, trucks, buses, and forklifts, mostly at 350 bar. For ships, trucks, trains, and even aircraft, hydrogen storage in liquid form (LH_2) also seems possible as an alternative, which would benefit their range (Figure 6) [42].

BEVs

In contrast to FCEVs, BEVs can be expected to take significantly longer to charge/refuel. This depends on the available charging infrastructure, the battery capacity installed in the vehicle, and its charging converter for AC charging or DC fast charging. Depending on the charging power, a full charge takes between 20 min (DC fast charging of up to 80 % of battery capacity) and several hours.

BEVs are charged using either AC or DC charging stations. In the case of AC charging stations, the chargers are installed in the vehicles, with a maximum charging power of 3,7 kW for single-phase systems and up to 22 kW for three-phase ones. Charging equipment can comprise either simple charging stations such as wallboxes or charging columns. The charging times vary depending on the charging power, the degree of charging, and the battery capacity.

With house connections and charging powers of up to 11 kW, even with relatively small battery capacities (e.g., the Nissan Leaf with a 30 kWh battery), several hours of charging time can be assumed for a full charge to be achieved. As Figure 7 shows for the Tesla Model S, a charging time of 37 h to 23 h can be assumed for a full charge of an 85 kWh battery when using wallboxes and charging stations with small charging capacities (i.e., 2,3 kW to 3,7 kW). For larger charging powers (11 kW to 22 kW), it is still 8 h to 4,5 h. By comparison, the H_2 refueling time for passenger cars is between 3 min and 5 min. In this context, it must be taken into account that passenger cars in Germany spend an average of 95 % of their time stationary and when they are, a connection to the grid is often available.

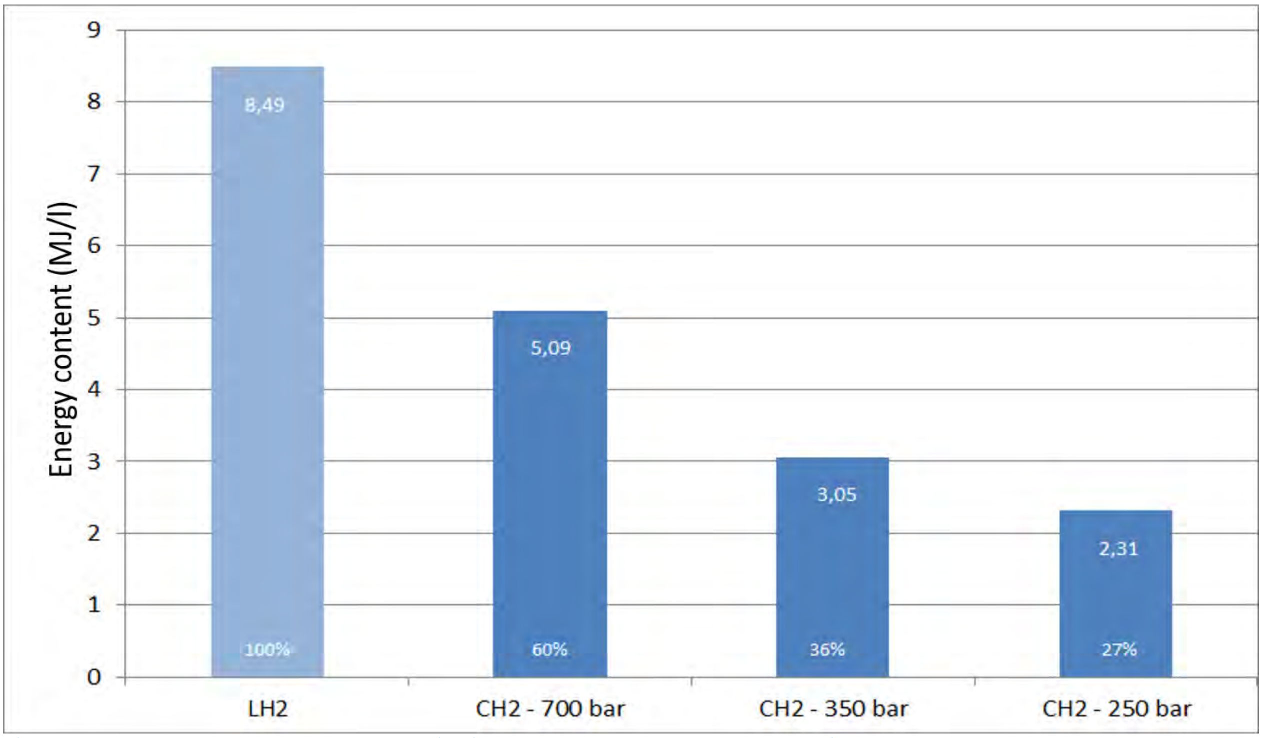

Figure 6. Energy content (MJ/l) of liquid and gaseous hydrogen at different pressures (source: ZBT GmbH)

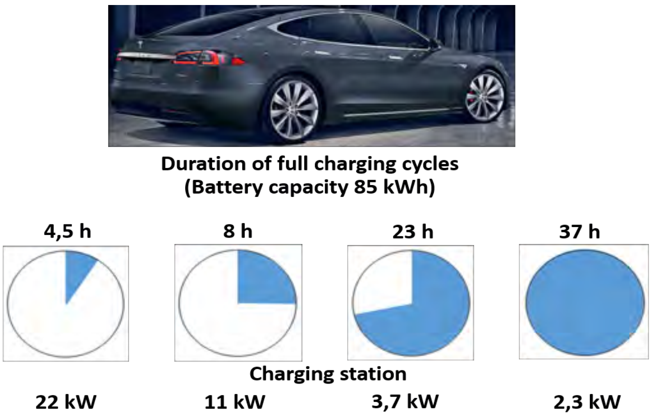

Figure 7. Duration of a complete charging cycle (battery capacity: 85 kWh) for the Tesla Model S (source: Inecs GmbH, based on [44])

Size and weight considerations militate against onboard charging power levels greater than 22 kW. Therefore, public DC fast charging stations are increasingly being used. These are located, for instance, at freeway filling stations and have various connection options (e.g., triple chargers), so that both AC charging and DC fast charging are possible (Figure 8) [45].

Figure 8. Type 2 charging station (AC) – CHAdeMO (DC) – Combo-2 (DC) (source: DEW21)

In the case of high range requirements, the long charging times speak in favor of the installation of DC fast charging facilities, which can drastically reduce overall charging times. This is reflected in the number of charging facilities in operation worldwide. In 2016, there were over 200.000 standard public charging stations and more than 100.000 fast charging facilities around the world, of which just under 17.000 and 1.500, respectively, were in Germany [15]. It should be taken into account that higher discharge and charging rates, as well as higher depths of discharge, tend to lead to increased degradation rates of batteries, which in turn can lead to an increase in battery capacity [46].

The charging power of DC fast charging stations is currently 50 kW or even more; in the future, up to 350 kW will be available. This corresponds to a charging current of 350 A at a charging voltage of 1.000 V. The high charging currents lead to higher heating of the charging cables. One way to reduce the resulting efficiency losses is to cool the charging cable. The manageability of the charging cable should not be neglected due to the high conductor cross-section required for the high currents.

With charging times of approximately 20 min and 350 kW of charging power, ranges of at least 300 km would be possible. However, it must be taken into account that the maximum possible charging power depends on the current state of charge (SOC), the state of health, the cell temperature, and other factors affecting the battery and vehicle. For instance, above 80 % SOC, the charging power is reduced in order to protect the battery.

Table 2 describes the AC and DC charging capacities and charging methods for various electric vehicles [47]. It should be noted that the charging powers specified here are not always achieved, depending on the SOC of the batteries and the mains connection. It should also be noted that the specifications for single-phase charging powers of 6,6 kW and above are only valid for the US and Asian markets.

Table 2. Battery capacities and AC and DC charging powers and charging methods for various BEV [47]

Vehicle/Manufacturer	Range (NEDC a)/WLTP a))	Capacity in kWh	Consumption in kWh	AC charging in kW	AC (phases)	DC charging in kW
Tesla Model S 100D d)	632	100	n.a.	11 (16,5 c))	3	120
Tesla Model X 100D d)	565	100	n.a.	11 (16,5 c))	3	120
Opel Ampera-e	520	60	n.a.	7,2	1	50
Renault Zoe Z. E. 40 d)	400	41	n.a.	22 (43c))	3	–
VW e-Golf	300	35,8	12,7	3,6 (7,2)	1 (2)	40
BMW i3 (94 Ah)	290	33	13,6	3,6 (11 c))	1 (3)	50
BMW i3s (94 Ah)	280	33	14,3	3,6 (11 c))	1 (3)	50
Hyundai Ioniq	280	28	11,5	6,6	1	70
Renault Kangoo b)	270	33	n.a.	7	1	–

Table 2. Battery capacities, as well as AC and DC charging powers and charging methods for different BEVs [47] (continued)

Vehicle/Manufacturer	Range (NEDC [a]/WLTP [a])	Capacity in kWh	Consumption in kWh	AC charging in kW	AC (phases)	DC charging in kW
Nissan Leaf	285 (WLTP)	40	19,4	6,6	1	50
Ford Focus	225	33	16,4	6,6	1	50
Kia Soul EV	250	30	14,3	6,6	1	70
Mercedes B250 e	200	28	16,6	11	3	–
Citroen Berlingo L1b)	170	22,5	17,7	3,6	1	50
Nissan e-NV200 Evalia	280	40	16,5	6,6	1	50
Peugeot Partner Tepee	170	22,5	n.a.	n.a.	1	50
Peugeot Partner L1b)	170	22,5	17,7	3,6	1	50
Nissan e-NV200b)	280	40	16,5	6,6	1	50
smart ed fortwo	160	17,6	12,9	4,6 (22 c))	1 (3)	–
VW e-up!	160	18,7	11,7	3,6	1	40
Mitsubishi EV	160	16	13,5	3,6	1	50
smart ed forfour	155	17,5	13,1	4,6 (22 c))	1 (3)	–
Citroen C-Zero	150	14,5	12,6	3,6	1	50
Peugeot iOn	150	14,5	12,6	3,6	1	50
Renault Twizy	100	6,1	n.a.	2	1	–
Citroen Berlingo Multispace	170	22,5	n.a.	n.a.	n.a.	n.a.
e.GO Life 60d)	194	23,9	11,1	3,6	1	–
smart ed fortwo cabrio	155	17,6	13,1	4,6 (22c))	1 (3)	–
Citroen E-Mehari	195	30	n.a.	n.a.	1	–
Jaguar I-Pace	480 (WLTP)	90	21,2	7	1	100
Hyundai Kona Bektrod)	482 (WLTP)	64	14,3	7,2	1	–

a) NEDC: New European Driving Cycle; WLTP: Worldwide Harmonized Light-Duty Test Procedure.
b) Vans/commercial vehicles (exceptions so far) – Kangoo and Partner with larger load volumes available in configurator.
c) Optional/surcharge, Renault not available in DE.
d) Larger battery selected.
n. A. not specified.

In addition to wired charging facilities, the deployment of inductive charging systems is being considered. Two coils – one in the parking area and one on the vehicle floor – are required for this, whereby an exact positioning of the vehicles above the primary coil in the parking area will be necessary for efficient transmission. The goal is to achieve an energy transmission efficiency of > 95 %. In the future, charging while driving, e.g., via a separate lane on the road, could also be possible [49]. However, this will require considerable investment in the expansion of the road network.

Uniform plug connection worldwide

Broad user acceptance of electric transportation requires uniform standards. At least in the case of pure battery-electric transport, this is not yet the case in all areas.

FCEVs

There is a uniform global standard for H_2 refueling. Based on the pressure levels of 350 bar and 700 bar, the same tank systems are available worldwide for the refueling of FCEVs. Country-specific adaptations with regard to the tanks' design and dispensing points are not necessary.

BEVs

With respect to BEVs, charging connections have not been standardized thus far. Differences in the BEV and PHEV segments exist in both the areas of output or charging power and electrical connection (plug-type). The Combined Charging System (CCS) has been defined as a binding standard by the EU within the framework of a directive (in Germany, this is laid out in the Ordinance on Charging Columns). In addition, there is also the CHAdeMO standard; Japanese and French vehicles in particular are equipped with this system. The disadvantage is that these systems are not compatible with one another. Therefore, public charging stations are now equipped with several plug-in systems (Figure 9).

There are three different plug types for AC charging stations alone. The permissible charging power varies from the AC house connection (230 V or three-phase current) to the DC fast charger. Furthermore, the types differ according to the sales markets, as well as in relation to the manufacturers (Figure 9).

FCEVs have greater ranges with a greater payload at the same time

The fuel consumption of electric vehicles is usually specified per 100 km of distance driven, analogous to internal combustion engines. This key figure is also used in this study for FCEVs and BEVs.

Figure 9. Overview of the different BEV connector types and associated standards (source: PHOENIX CONTACT)

[1] The type 1 standard for North America does not provide for a charging plug on the infrastructure side. In Europe, an adapter cable is used for this case, which consists of a type 1 charging plug on the vehicle side and a type 2 charging plug on the infrastructure side.

FCEVs

FCEVs are characterized by the fact that power and energy storage are decoupled. The range increases with the size of the tank. Accordingly, FCEVs are comparable to conventional vehicles in terms of range. Distances of 800 km can be covered using normal 700 bar H_2 tanks [50].

BEVs

The range of BEVs depends on the battery capacity: The greater the capacity of the battery, the greater the range [50]. It must be taken into account here that, in contrast to FCEVs, in BEVs the energy stored in the battery correlates with the total power.

Typical range

FCEVs and BEVs have proven their technical suitability for everyday use many times over. Their driving behavior is comparable to that of conventional automatic vehicles. Cold-start capability is not a problem for all ZEVs, either. For FCEVs, the manufacturers assume that an outside temperature of at least –20 °C is not problematic. For the Toyota and Hyundai vehicles, even –28 °C is mentioned.

Various vehicles were compared within the framework of the Federal Government's Electromobility Showcase. This showed that luxury class vehicles with a battery capacity of 85 kWh can cover distances of up to 390 km. Small cars that are primarily used in city traffic, and have much smaller battery capacities. The achievable distance is then usually around 100 km.

Particularly for long-distance travel, hydrogen-powered systems offer range advantages, as otherwise very large and heavy batteries would be required. Comparable advantages also apply to their ability to transport large payloads. Furthermore, FCEVs lose less payload capacity than BEVs for larger and heavier vehicles with higher energy consumption rates. Above a certain energy demand, the total cost of energy storage and conversion is also lower for FCEVs. This is because both the weight and cost of the hydrogen refueling system does not increase as steeply as that needed for batteries as the energy content increases [51].

A challenge with regard to BEVs and FCEVs is the increase in gravimetric energy density (i.e. the amount of energy that can be stored in relation to the tank weight, in %). Based on a typical 700 bar tank for 4 kg to 5 kg of H_2, the gravimetric energy density today is 7 % [53], corresponding to a tank weight of 57 kg to 72 kg. By comparison, the volumetric and gravimetric energy densities for the lithium-ion battery systems commonly used in passenger cars are about 100 Wh/l to 250 Wh/l and 60 Wh/kg to 140 Wh/kg, respectively [51]. Figure 10 underlines the differences to conventional internal combustion engines [54]. Despite the efficiency advantages of the fuel cell and especially the battery compared to conventional combustion engines, the complete energy storage system (battery or H_2 tank) must be expected to weigh more for achieving the same range. This applies in particular to battery systems.

A direct comparison of the pure consumption figures of BEVs and FCEVs appears to be difficult, as the battery vehicle models available in the market, such as the best-selling BEV, the Nissan Leaf, tend to be in the small- to medium-sized vehicle range, whereas the fuel cell vehicle models tend to be in the medium-large to SUV range. The conversion losses – especially in hydrogen production – must also be taken into account in mapping the entire efficiency chain.

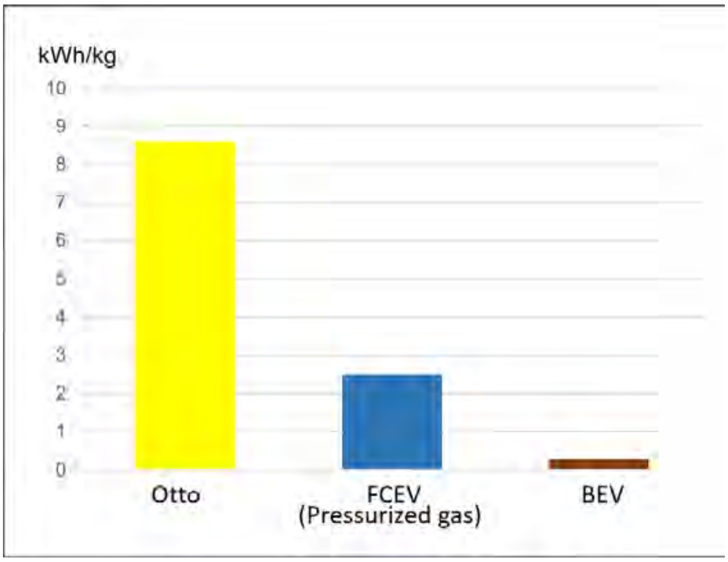

Figure 10. Gravimetric energy density of different tank systems (source: Shell)

Table 3. Comparison of typical key figures of representative FCEVs and BEVs [55] (source: University of Hanover)

	Size class	Motor in kW	Tank volume	Empty weight in kg	Range in km according to EPA	Consumption car in kWh/100km	Consumption in kWh/100km related to the power grid
Toyota Mirai	medium	113	H_2: 165 kWhH_2 Batt.: 1,6 kWhel	1.850	502	33,33 kWhH_2	56-67
Tesla Model S	large	235	Batt.: 75 kWhel	2.108	401	21,12 kWhel	24-27
Nissan Leaf	medium	80	Batt.: 30 kWhel	1.573	172	16,77 kWel	19-22

Table 3 compares three typical ZEVs, whereby the calculation of the consumption values is based on the efficiency values shown in Figure 12. In terms of product characteristics, above all range and comfort, the Toyota Mirai and Tesla Model S (75 kWh) are the most comparable, although the Mirai, like all other FCEVs, has thus far only been produced in small numbers. The consumption figures make it clear that the loads on the electricity generator side for FCEVs, including hydrogen production, at 56 kWh to 67 kWh per 100 km (EPA driving cycle) are about 2,3 times higher than for pure battery vehicles. Using electrolyser and fuel cell waste heat would have a positive impact on the balance of the hydrogen option and compensate for some of the battery's efficiency advantages.

The range of FCEVs is largely independent of environmental conditions and almost constant over the life of the vehicle

A positive factor of FCEVs is the reduced influence of environmental conditions on their range. High or low temperatures have only a minor effect on the operating behavior of fuel cells. Low temperatures only result in longer heating times until the optimal operating temperature is achieved, and possibly higher consumption by the auxiliary units. A vehicle from the North Rhine-Westphalia (NRW) Energy Agency (a Daimler B-Class F-Cell), for example, tends to feature an additional consumption of 10 % in winter and – 10 % in summer relative to the average value of 1,09 kg H_2/100 km at 85.000 km driven.

In contrast, lithium-ion batteries are sensitive to lower and higher temperatures (< 10 °C and > 40 °C), such that on the one hand their usable capacity decreases and on the other, accelerated ageing behavior can be assumed.

For the practical suitability of a system, statements on the service life are also of interest. As electrochemical processes are involved in both batteries and fuel cells, ageing (degradation) occurs in each case.

FCEVs

In fuel cells, depending on the operating time, a drop in efficiency, i.e., degradation, occurs, among other processes, as a result of contamination of the catalyst layers of the membrane electrode assembly (MEA). This effect can be further reduced with new air filter technologies and intelligent operating strategies. From today's perspective, at least 4.000 operating hours can be assumed for commercially-available systems. The development goal is a service life of about 7.000 operating hours, comparable to that of conventional vehicles. In real-world operation, fuel cell buses have already achieved DOE targets of 20.000 driving hours [9] or 25.000 driving hours [10]

Fuel cell performance degrades during vehicle operation as the operating time increases. As a result, consumption deteriorates towards the end of the service life. A meaningful database for a quantitative statement on this increase in consumption is not (yet) available due to the small current fleet sizes. There is therefore a need for further research in this area.

BEVs

The range of a BEV is a function of its battery life. As the battery ages over its service life due to electrochemical factors, this has a negative effect on the battery's capacity and the range decreases accordingly.

Batteries exhibit complex aging behavior. At high and low temperatures, high states of charge, as well as charging and discharging rates, accelerated ageing, and thus a shorter service life can be assumed. This can be partly avoided by on-board cooling systems, such as those used by Tesla. Onboard battery thermal management is therefore essential in BEVs to preserve the battery's properties. Furthermore, intelligent battery management systems for the different battery types are currently being developed to optimize operating behavior.

Reliable statements on the ageing behavior of batteries are currently only available from a few manufacturers. According to the Japanese manufacturer Nissan, the battery of an electric car should retain at least 70 % of its original capacity in the first five years or over the first 100.000 kilometers. If the value falls below this limit, the battery must be replaced or overhauled [56]. For some users, a correspondingly reduced range will probably also be sufficient for daily transportation needs.

Real-world experience suggests that the charging process has a great influence on the operating behavior of batteries. In particular, frequent charging of a battery at low temperatures has a negative effect on the service life of Li batteries. Completely discharging and then fully charging the battery (i.e., carrying out full load cycles) also has a negative influence on ageing behavior. Instead, it is advantageous for the service life to operate the battery in a medium state of the charge range, which in practical terms would mean a greatly reduced range [57].

Heating in the winter and cooling in summer are possible in FCEVs without battery support

The heating and cooling of electric vehicles requires special measures compared to conventional ones:

- BEVs draw the energy needed for heating from the battery, which in turn affects the range. In the winter, an additional consumption of 30 % is observed to enable the heating of electrically-powered vehicles [58]. The extent to which this can be compensated for with innovative solutions, e.g., superior windows, thermal insulation, more efficient heating systems, heat pumps [59], etc., is currently still under discussion.

- In FCEVs, the available waste heat from the fuel cell is sufficient to heat the vehicle during normal operation. If necessary, a supplementary heating system can be used.

- With respect to cooling, the air conditioning unit in FCEVs and BEVs is electrically-driven. FCEVs obtain the energy to drive the cooling system from the hydrogen tank via the fuel cell. A restriction of the driving capacities, if noticeable, is comparable to that of today's vehicles with internal combustion engines. BEVs, on the other hand, draw the energy needed to drive the cooling system from the battery, and so the range is also affected.

The efficiency of BEVs is greater than that of FCEVs

The basic design of FCEVs and BEVs was already addressed at the beginning of Section 4.2. Given that FCEVs, like BEVs, utilize batteries, it is also possible to recover braking energy in fuel cell vehicles.

With regard to the charging losses of BEVs, they depend on the onboard chargers or DC fast-charging stations and the battery temperature, among other factors.

According to Siemens, an efficiency of > 94 % at a rated output of 417 V/120 A can be assumed for a DC fast-charging station [62[62]ABB also reports an efficiency of 94 % at the rated output power [63]. However, these figures do not take into account the charging losses that depend on the current charging power and battery temperature. For onboard chargers, an efficiency of approximately 94 % at nominal power can also be assumed.

In addition, standby losses must be taken into account for DC fast-charging stations. As presented by PricewaterhouseCoopers [60], charging losses are to be estimated at an average of 20 % of the energy input and, according to the Wuppertal Institute [61], at 10 % to over 30 %.

Figure 11 shows the dependence of the efficiency on the charging power of an onboard charger with a nominal power of 22 kW [64]. The extent to which a similar curve can be assumed for DC fast-charging stations must be left to further experience. At very high charging powers, the battery may need to be cooled, which has a negative effect on its overall energy balance.

For an efficiency comparison of FCEVs and BEVs, the schematic process flows shown in Figure 12 are used. These describe the complete process chain from the electrically-supplied energy (here, from renewable sources) to the final car consumption for typical BEV and FCEV passenger cars. When evaluating the efficiency chain, it must be taken into account that additional influencing variables such as energy storage, sector coupling, etc., are also taken into account (see Sections 4.3 and 4.4), which are not considered here. These can improve the efficiency of FCEV systems.

The values assumed in this presentation are based on [65] and our own assumptions/experiences. In addition, the respective ranges of some relevant processes are added for better illustration, and derive from different technologies, applications, framework conditions (e.g., outdoor temperature), as well as assumptions and sources. On the BEV side there are, above all, relatively large ranges between slow and fast charging stations, which tend to be more efficient. On the hydrogen side, this applies to the areas of electrolysis, compression, and transport.

The main advantages of batteries are their higher efficiency and the simpler system design. Electrical energy is charged directly into the batteries via charging stations and retrieved for driving as needed. The overall efficiency of a vehicle (without taking into account electricity generation and upstream grids) is thus only dominated by the losses in the battery during charging and discharging, as well as by the losses of the power converter used in each instance. The above-mentioned grid losses (transmission) can be significantly reduced by using locally-generated renewable electricity (PV or wind).

Figure 12 takes into account the typical values for losses in power transport, energy conversion, and drive technology. More precise and individual are vehicle-specific consumption values, which greatly depend on the type and selected driving cycle. Nevertheless, correlations can already be recognized, e.g., with the vehicle weight, as is shown in Table 3, on the basis of representative models. The size class, range and consumption refer here to the EPA [66], tank volume, and battery capacity in accordance with the manufacturer's specifications.

These relationships are reflected in the following figures regarding vehicle consumption. The consumption figures for a BEV-Ford Focus Electric (Figure 13) and an FCEV-Toyota Mirai (Figure 14) are shown for different distances, temperatures, and clusters. The results confirm that the energy consumption of BEVs highly depends on the outside temperature.

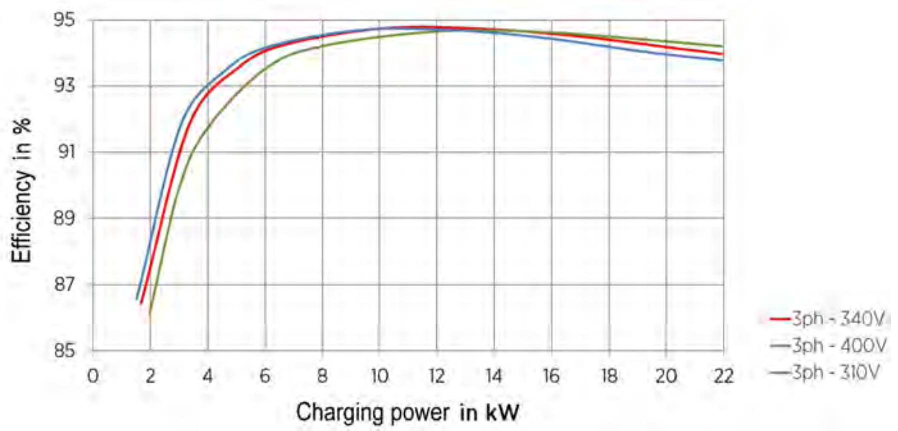

Figure 11. Efficiency as a function of charging power (source: BRUSA Elektronik AG)

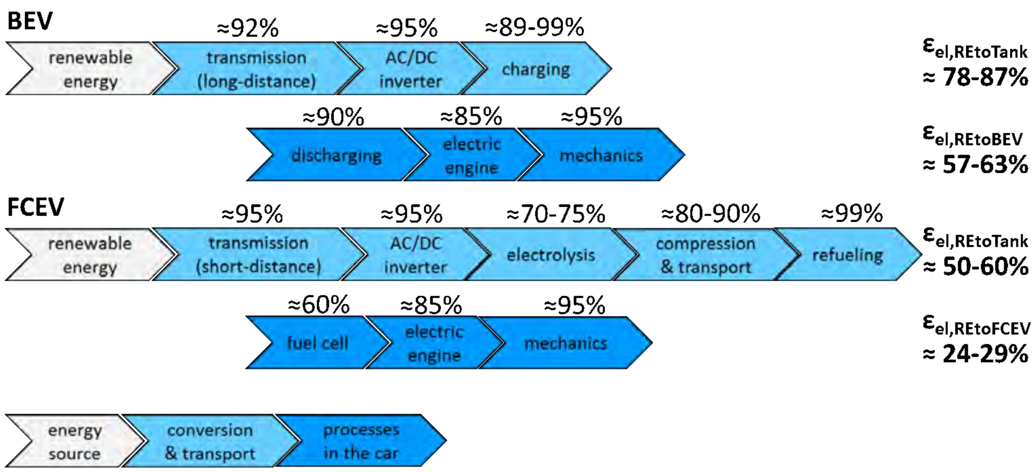

Figure 12. Electrical efficiency chain (source: University of Hanover)

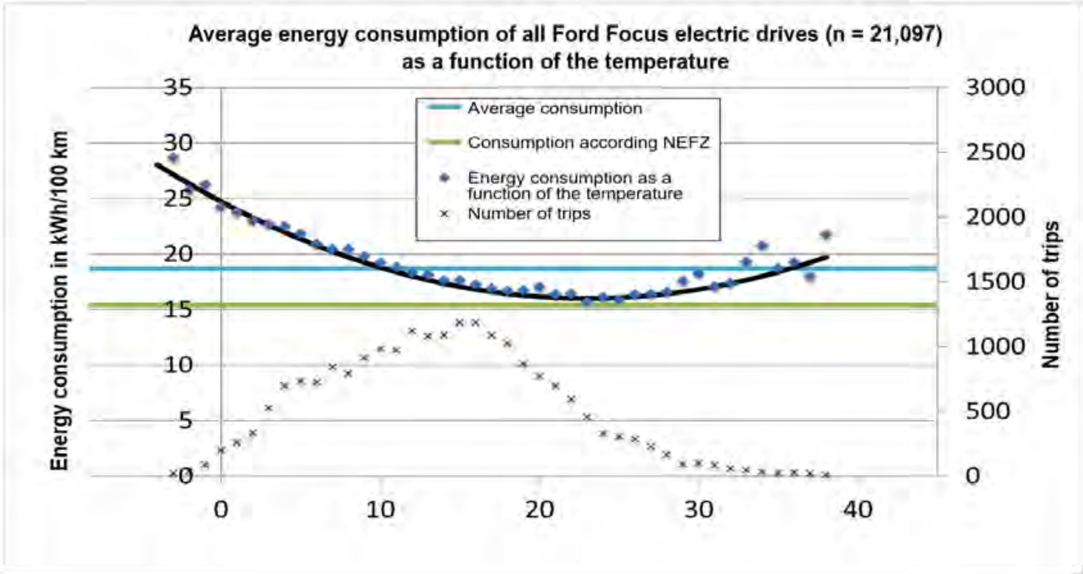

Figure 13. Mean energy consumption of all Ford Focus Electric trips (*n* = 21.097) as a function of outdoor temperature (source: CologneEmobil II [67])

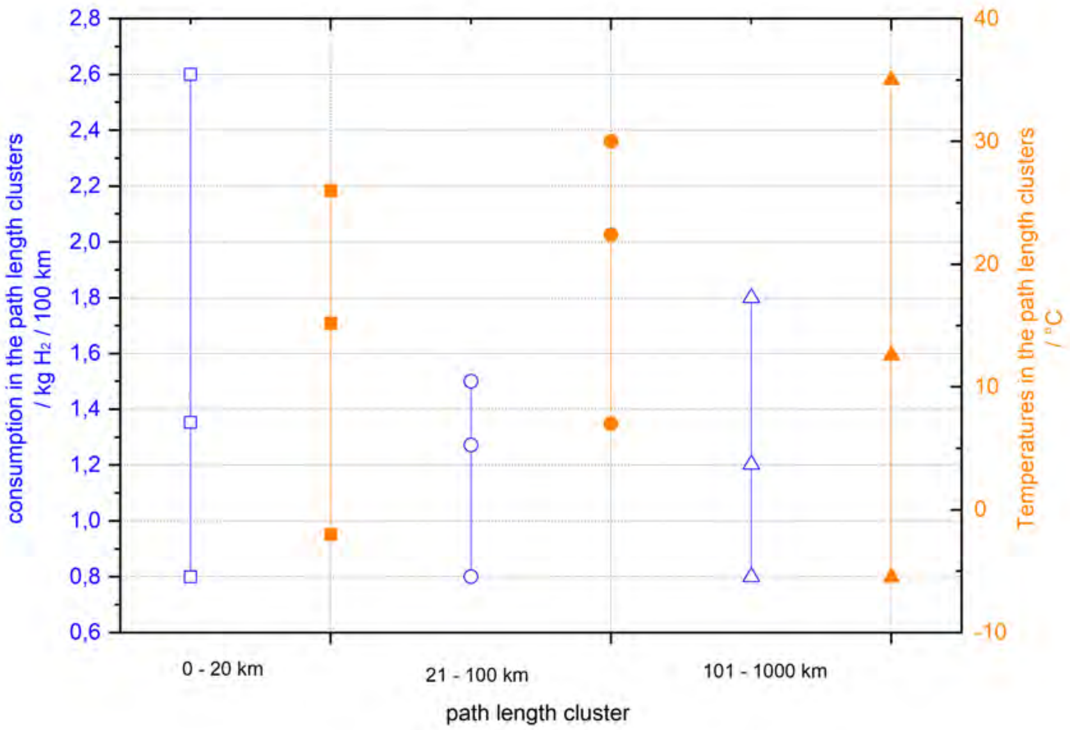

Figure 14. Toyota Mirai overview of real consumption and ambient temperature (source: Fraunhofer ISE)

4.3 Infrastructure

Core statements

- By using hydrogen produced on a large scale and expanding existing fueling station facilities, a rapid adaptation of the hydrogen infrastructure is possible. In the medium- to long-term, as with the charging infrastructure for BEVs, a gradual expansion of production and transport systems can be achieved.
- Due to the on-site storage of large quantities of hydrogen at fueling stations, demand peaks with the full utilization of the filling station will be unproblematic.
- With their low market penetration, infrastructure investments for BEVs will be lower. With a high market penetration, lower costs for H_2 infrastructure can be assumed, depending on the assumptions.
- H_2 transportation is usually affected by truck. In future, if there is greater demand, it will be possible to convert existing natural gas pipelines for exclusive H_2 transport.
- The provision of liquid hydrogen (LH_2) will lead to technically-simpler fueling stations, as the complex gas compression, pre-cooling, and quality analyses can be omitted. The amount of H_2 transported in a trailer can be increased to 4 t (a factor of 3 to factor 3,5 compared to pressurized gas transport).

The widespread introduction of electric transportation will require the development of a corresponding infrastructure. This applies equally to FCEVs and BEVs.

A characteristic feature of FCEVs is that the refueling process be preceded by a conversion process that will be used to produce hydrogen from renewable electricity by means of water electrolysis. This conversion process can take place in a centralized or decentralized manner using smaller electrolysers in the vicinity of the fueling stations.

With battery-powered vehicles, on the other hand, the direct use of electrical energy from the public power grid is possible. Alternatively, the use of stationary storage units from which BEVs draw their energy is an option for relieving the strain on the grid. However, this is associated with a loss of efficiency.

The use of hydrogen allows rapid adaptation of the infrastructure

The widespread use of electric vehicles requires the use of renewable energy in order to achieve the climate change mitigation targets. With its decisions regarding the energy transition, Germany has created the prerequisites for this. In addition to the increased use of renewable energy technologies and the expansion of high-voltage direct current transmission (HVDC), which enables electricity to be transported from the north to the south of the country, this concerns the development of an intelligent electricity grid (smart grid).

The pathway based on hydrogen as a chemical energy carrier enables the integration of another essential infrastructural component, namely the gas grid. With a transmission capacity of approximately 20 GW per line in the high-pressure grid, it is significantly higher than that of the electricity grid.

By making use of comprehensive information systems that inform consumers about the current electricity procurement situation, it will also be possible to utilize demand-optimized electricity offers for H_2 generation and vehicle charging. However, this will require suitable charging facilities (e.g., wall boxes and fast-charging facilities) as well as suitable billing procedures.

FCEVs

The comparison of H_2 fueling stations and charging stations shows that the refueling capacity of almost 3 MWH_2 is significantly higher than that of fast charging stations, with approximately 350 kWel. Within a given period of time, significantly more FCEVs can be supplied per dispenser than BEVs per charging point, which means that many vehicles can fill up in succession at a dispenser within a certain period of time. By comparison, BEVs require a large number of charging stations to enable the simultaneous charging of a comparable number of vehicles during the same period. This also applies to the use of DC fast charging stations. Although they shorten the charging times, here, too, in comparison to FCEVs, the charging times are 3 to 5 times longer compared to FCEVs when limited to 80 % of battery capacity. Therefore, a correspondingly larger number of parking spaces with charging facilities must be provided in order to achieve the same refueling capacity.

The expansion of H_2 refueling stations is relatively simple, as corresponding refueling systems can be realized in the vicinity of conventional refueling stations. Experience from realized projects (see Berlin

Heerstraße, for example) [68] suggests that H_2 refueling facilities can be built by expanding existing refueling stations. This would offer the advantage that the search for a location could be partially eliminated and the portion of the infrastructure available at the fueling station could also be used for H_2 refueling.

The capacity design of hydrogen fueling stations follows an approach comparable to that of today's stations. The space requirements of H_2 fueling stations also do not significantly differ from those of today's petrol and diesel fueling stations. Depending on the H_2 delivery concept, however, it must be assumed that more space will be required due to the necessary H_2 storage at the fueling stations. During market launch, H_2 delivery may take place with the help of trucks. In the case of a high regional density, pipeline delivery offers some advantages.

The hydrogen infrastructure available today does not yet allow for the large-scale deployment of FCEVs. Due to the high investment costs and small fleet sizes, the expansion is currently taking place only hesitantly. An expansion of the fueling station network could support the market ramp-up and ultimately market penetration of FCEVs.

By February of 2018, 328 hydrogen fueling stations were available worldwide for the supply of fuel cell vehicles, of which more than 250 were publicly accessible (meanwhile additional stations have been realized). These were mainly distributed across Europe, with 139 (especially in Germany, with 45), followed by Asia, with 118 (especially Japan, with 91) and North America with 68 (especially in the USA, or California, with 40). With more than ten new fueling stations having gone into operation in Germany alone by the beginning of November 2018, and China aiming to have 100 stations in operation by 2020 (currently it has 12), the number of fueling stations worldwide is already significantly greater today.

Until 2015, the expansion of H_2 fueling stations in Germany was driven with the support of the Clean Energy Partnership (CEP). In this consortium, partners from industry and the public sector worked together to prepare the market for transportation utilizing hydrogen and fuel cells, in the spirit of a sustainable energy transition. In 2015, the joint venture "H2Mobility" was founded, which has since taken over the majority of the existing public car fueling stations in Germany and is building additional stations at an increasing pace (see Figure 15). The goal is a nationwide distribution of a basic hydrogen infrastructure in order to supply fuel cell-powered passenger cars. By November 2018, 52 public fueling stations were already available in Germany and 42 more were under construction [69; 70]. Up to 400 stations are to be built in a second expansion phase by the end of 2023 [113]. A prerequisite for this, however, is an increasing demand for FCEVs. Figure 16 shows the regional development of the hydrogen infrastructure [71].

The expansion of H_2 fueling stations in Germany is complemented by activities in neighboring countries, especially Denmark. Here, too, ten fueling stations are already available and more are being planned. Likewise, Austria and Switzerland already have several stations in operation. More are planned there as well, and so the conditions are already in place to bridge even longer distances without refueling issues.

BEVs

The provision of an area-wide charging infrastructure is accompanied by an influence on the loads of the electricity grids. If many BEVs are simultaneously charged at a local grid station, local overloads in the low-voltage grid can occur with uncontrolled charging [72]. However, with controlled charging – even with higher charging capacities – the demand can usually be met, even with a high penetration of BEVs and without a nationwide grid expansion.

The free capacities of the distribution grids are currently used to supply charging stations. With further market penetration, greater charging capacities due to larger battery capacities and faster charging processes, the power demand will increase. This would require, among other things, the installation of DC fast-charging stations at freeway service stations, as well as shopping centers and car parks as far as possible. At locations with a high expected simultaneity factor, e.g., theaters, concert halls or sports venues, expansion of the low- and medium-voltage grids is necessary.

The charging capacities of DC fast-charging stations will reach 100 kW to 350 kW in the future and be available in a variety of locations. This requires medium-voltage (MV) connections, which in many cases require considerable investment for line extension and possibly also the construction of new substations. However, it is difficult to estimate the costs for a charging station, especially for DC fast charging ones. In addition to the costs of the charging station, the existing grid infrastructure plays a significant role here.

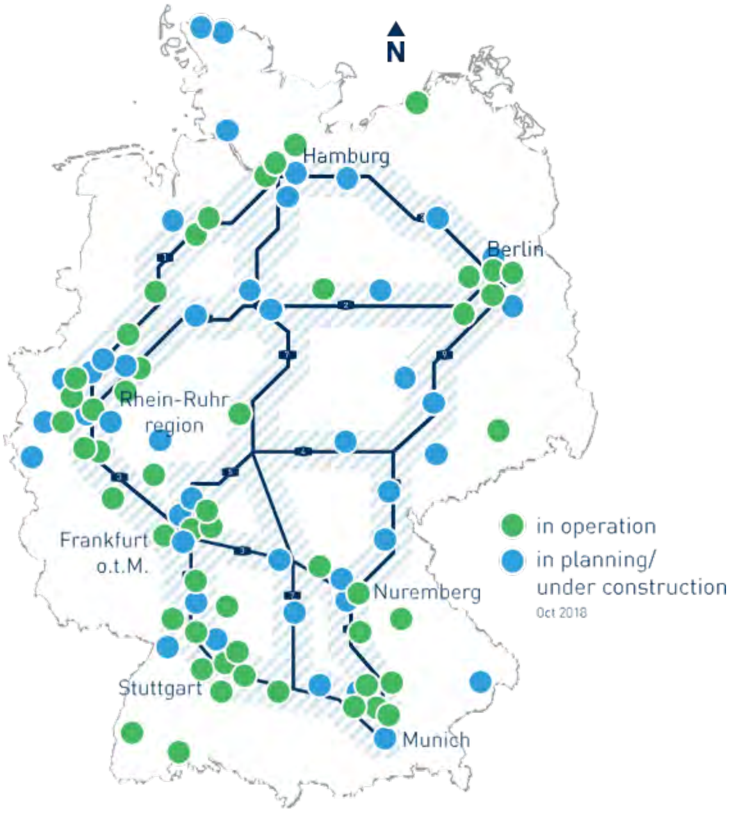

Figure 15. Existing (green) and planned (blue) H_2 fueling stations in Germany (source: H2Mobility, https://H2.live)

Figure 16. Development of the H_2 infrastructure in Germany (source: H2Mobility)

One possibility for relieving the strain on the grid is controlled charging. However, a prerequisite for this is the acceptance of vehicle users with respect to the control of the charging processes by the grid operator. Furthermore, the regulatory requirements regarding power and time control by the grid operator are lacking [73].

Bidirectional charging and discharging of vehicle batteries (vehicle-to-grid [V2G]) offers the possibility of optimizing the load flow. However, this requires a technical expansion of current charging stations and vehicles.

Park & Ride car parks would be interesting locations for the installation of charging facilities. Here, in particular, there are opportunities for controlled charging, as the standing times of the vehicles could be relatively reliably estimated.

When charging vehicles, it must be ensured that a user can obtain electricity from a supplier of his choice, which requires suitable billing procedures ("roaming"), which are currently being developed in Germany and other European countries.

Investment costs for an H_2 infrastructure are lower than for a BEV supply

As part of a study by the Institute of Electrochemical Process Engineering at the Jülich Research Centre and the Chair of Fuel Cells at RWTH Aachen University [74], an attempt was made to evaluate the cost of setting up an H_2 refueling and electricity charging infrastructure by means of a scenario analysis. Comparison criteria include investments, costs, efficiencies, and emissions of the respective infrastructures, whereby a distinction was made between supplying several hundred thousand and several million vehicles with electricity or hydrogen. In the case of the hydrogen variant, options for the integration and storage of electricity surpluses that will arise in the future in energy systems dominated by renewable energy were also considered in particular (Figure 17).

Scenario assumptions

- The share of electricity renewably generated is 80 %.
- With regard to hydrogen, the transition phase involves the conversion of gas production from fossil energy to the use of surplus renewable electricity. It is accompanied by the construction of seasonal hydrogen storage facilities to bridge a period of 60 days. In the initial phase, higher investments are necessary than in the case of the charging infrastructure.
- For smaller numbers of vehicles of up to a few hundred thousand, the costs of the charging stations and expansion requirements for distribution grids were taken into account for charging. Any necessary grid expansion in the transmission grid and seasonal storage were neglected.
- In the scenario with large stocks of ZEVs (i.e., 20 million vehicles), the H_2 supply also includes seasonal storage with a total capacity of 60 days' consumption, as well as the filling stations and logistical components. Salt caverns for H_2 storage were assumed as a storage option, by means of which large quantities (some 10 TWh) of renewable energy could be especially cost-effectively contained (0,2 €/kWh to 1 €/kWh).

Results of the scenario analyses

- For small vehicle stocks (up to a few hundred thousand), the investment in infrastructure development is almost the same for both technology pathways.
- With a high market penetration (20 million vehicles), the investment for a charging infrastructure was significantly higher, at around €51 billion, compared to the hydrogen infrastructure, at around €40 billion (Figure 18).

The specific costs per kilometer driven are approximately the same for both supply concepts at high market penetrations. They average 4,5 ct/km for electric charging and 4,6 ct/km for hydrogen. Given that the possibility of intermediate storage of hydrogen enables a more flexible use of electrical energy from renewable sources, the lower energy efficiency of the hydrogen path can be approximately compensated for by the fact that hydrogen is produced during times of generally low demand for electrical energy, which can therefore be purchased more cheaply.

For the scenario with 20 million fuel cell vehicles, 87 TWh of electricity are required annually at off-peak times for electrolysis and an additional 6 TWh of electricity from the grid (transport and distribution of hydrogen). Charging 20 million battery vehicles requires 46 TWh/a of electricity from the distribution grid. The electricity supply at times of low demand of 220 TWh to 270 TWh exceeds the demand to supply 20 million vehicles in both infrastructure pathways by a factor of three to six in the assumed energy supply scenario with high renewable shares (80 % estimated). As the supply of BEVs must also be ensured during the so-called dark period (usually two to three weeks), controllable power plants – with corresponding fuel reserves (if necessary also hydrogen or synthetic methane) – must be available for this purpose.

BEVs are characterized by the higher efficiency of the charging infrastructure and vehicles compared to H_2 and FCEVs. However, it must be taken into account that the flexibility of electricity demand for BEVs is limited to shorter periods of time.

By using renewable electricity surpluses and grid electricity with high shares of renewables, the kilometer-specific CO_2 emissions for both supply options are low compared to the use of fossil fuels (Figure 19). Hydrogen infrastructure with inherent seasonal storage can integrate higher shares of surplus renewable energy and therefore has an advantage in terms of CO_2 reduction. However, a charging strategy for battery vehicles based on the availability of renewable electricity can further reduce their CO_2 emissions.

Expansion of the H_2 network through the reconstituting of natural gas pipelines

The following options are available for the gas supply of H_2 fueling stations:

- The hydrogen is produced locally by means of electrolysers installed in the filling station area, recompressed and then stored in high-pressure storage tanks at pressures of up to 1.000 bar.
- The hydrogen is produced in larger factories and transported to distribution centers (fueling stations) by truck. Due to the higher energy density, transport in liquid form is recommended (with truck transport capacities of 4.000 kg of liquid H_2). However, delivery in gaseous form is also conceivable (transport capacity of up to 1.000 kg depending on the pressure stage).
- Hydrogen is transported by pipeline.

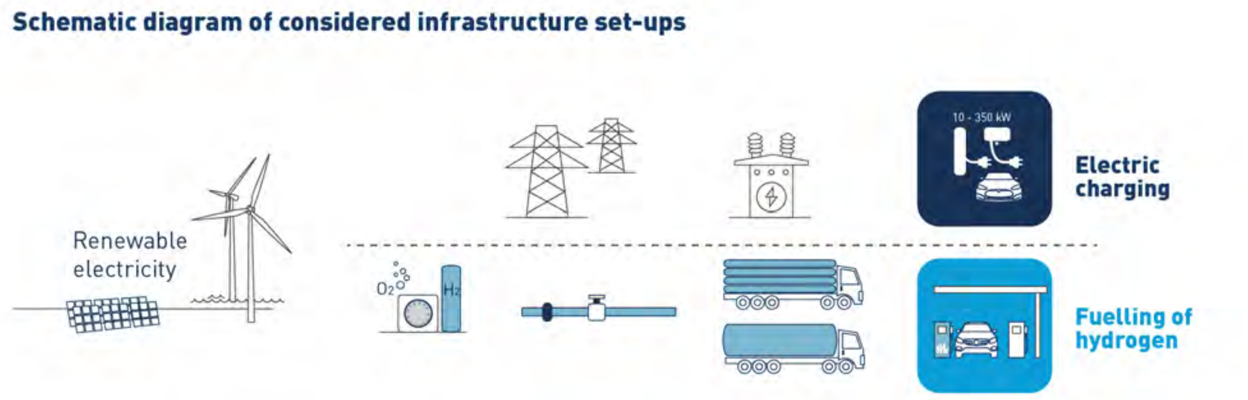

Figure 17. Schematic representation of the investigated supply infrastructures (source: H2Mobility)

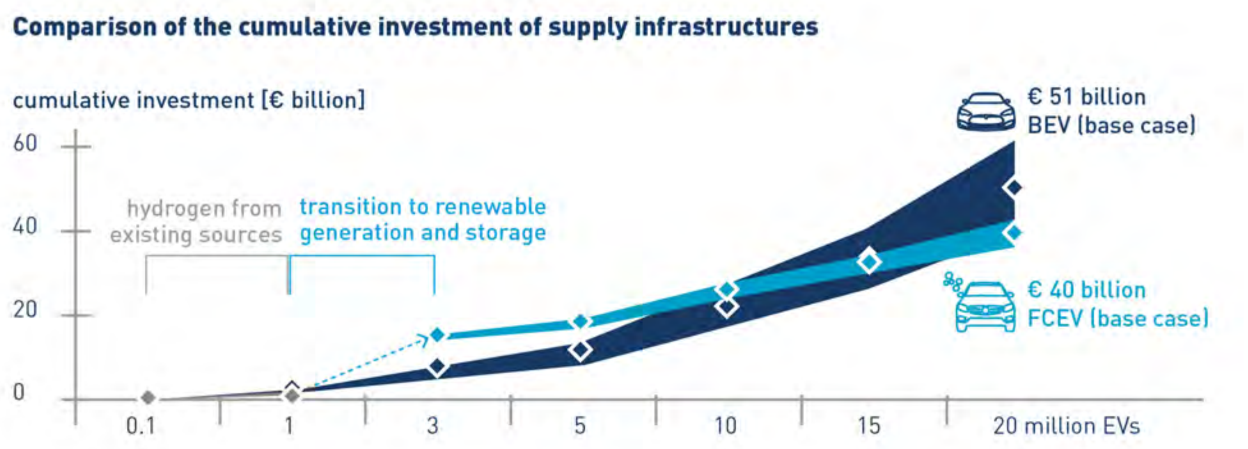

Figure 18. Comparison of cumulative investments for infrastructure development (source: H2Mobility)

In general, it is true that for large amounts of energy, transport by pipeline is superior to transport by road in terms of cost and performance. This raises the question of how a pipeline supply could be realized for H_2 at low cost.

In addition to making use of existing H_2 pipelines and building new ones, another option is to use existing natural gas pipelines. A simple technical option under discussion is the admixture of H_2 to natural gas. According to DVGW worksheets G 260 and G 262, the proportion is limited to approximately 10 % of the natural gas volume; larger amounts of energy would thus not be transferable. Studies by the DVGW-EBI, on the other hand, suggest that admixtures of up to 30 % are possible [75].

The admixture requires hydrogen and natural gas to be separated at the customer site, which would entail greater effort. Membrane processes could also be used to concentrate a small percentage of H_2 into pure H_2. Determining the economic viability of this must be left to future investigations. Alternatively, direct use of the mixed product could be considered.

Alternatively, it is under discussion to convert existing natural gas pipelines to H_2. Important, pioneering work in this regard is being performed within the framework of the East German Hypos project [76]. Amongst other things, this concerns the conceptual development, structuring and implementation of a technical distribution network infrastructure with house connection lines for carrying out research and development in the context of the pilot supply of a planned location (i.e., a “hydrogen village”).

Theses on infrastructure development for hydrogen-based transportation

The following theses are not supported by studies with robust data and facts. In particular, a variety of external factors, such as public acceptance (subjective risk assessment), regulatory aspects but also the enforcement power of individual manufacturers, can lead to significant deviations from the expected solution pathways.

1. **Hypothesis: Pressurized hydrogen logistics in the next five years: 350 bar and 500 bar semitrailers**

   The extremely small fleet of hydrogen-using transportation systems (cars, trucks, trains) will be supplied with pre-compressed CGH_2 (compressed gaseous hydrogen) within the next five years. Hydrogen fueling stations will have pressure tanks of various pressure levels, up to 1.000 bar, and their own complex H_2 compressors and low-temperature pre-coolers. The vehicles in turn will carry the hydrogen at high pressure, between 350 bar and 700 bar. Possibly, even higher pressures will be achieved in the passenger car sector in order to safely realize ranges > 500 km, even under unfavorable conditions.

2. **Hypothesis: With increasing fleet strength, compressed hydrogen (CGH_2) will be substituted by liquefied hydrogen (LH_2).**

Demand will initially be met by existing large-scale liquefiers. In addition, electrolysis plants will be operated at the existing sites.

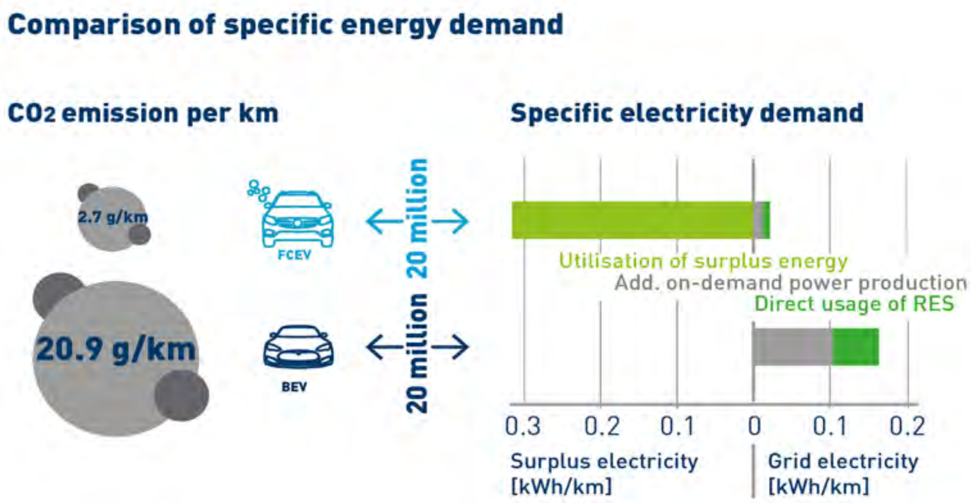

Figure 19. Comparison of CO_2 emissions and electricity requirements per kilometer (source: H2Mobility)

The growing demand for hydrogen is increasing logistical costs. Typical semi-trailer transport will span between 300 kg to slightly more than 1.000 kg of gaseous hydrogen per vehicle, with a gross weight of around 40.000 kg (CGH_2), depending on the pressure level. In contrast, up to 4.000 kg of liquid hydrogen (LH_2) can be transported per vehicle (Figure 20).

Another aspect is the fairly high complexity and energy requirements of a CGH_2 filling station, as well as the fact that, at high tank frequencies, the maximum pressure storage, which is small for techno-economic reasons, has a limiting effect.

By comparison, LH_2 fueling stations are much simpler and can guarantee short refueling times until the storage tanks are exhausted. Evaporation losses do not occur, or only to a subordinate extent, if demand is sufficiently high. The hydrogen onboard an FCEV can still be stored in gaseous form. It is also conceivable, however, that in the commercial vehicle sector (truck/train) with its high utilization, liquid hydrogen will also make a comeback and the CcH_2 Cryo-compressed Hydrogen Storage (BMW CcH_2) presented by BMW, with its energetic and technical advantages, will be utilized.

3. **Hypothesis: The production of LH_2 requires large central liquefiers, as no cost- and energy-efficient methods for liquefaction in small plants are currently known.**

The developing LH_2 system could show similarities to that of today's refineries, or even the preferential development of such sites. Logistically already developed, they need, however, a much stronger connection to the new raw material "renewable energy."

If LH_2 becomes a readily available product, other users, such as the aviation or chemical industries, can be added as customers.

4. **Hypothesis: In the long term, in addition to the electricity grid as a transport and distribution system for renewable energy, the existing gas grid will also be integrated or expanded.**

Hydrogen is already mixed into natural gas at levels of up to 10 % by volume. However, higher H_2 concentrations would require adaptation measures for a large number of consumers, could only be used within a narrow band and would need to be carried out again in the event of a further increase in concentrations. This mixed gas would not be suitable for electric transportation.

Gas network operators are therefore investigating the possibilities of transporting 100 % hydrogen by volume in existing pipelines. The advantage here would be that hydrogen would be preserved in its pure form with its numerous possible applications, especially for transportation, which requires pure hydrogen. With increasing sales volumes, the construction of new pipelines for gaseous hydrogen transport could also become economical.

4.4 Energy procurement

Core statements

Hydrogen procurement can generally be considered uncritical in terms of availability and costs (diesel-equivalent price range) from market introduction, to market ramp-up, to mass market. Nevertheless, the supply of green hydrogen to fueling stations in Germany, both in sufficient quantities and at reasonable market prices, is currently associated with problems and therefore requires a further expansion of production capacity for green hydrogen.

Figure 20. Road transport of hydrogen (source: Shell)

- Hydrogen is becoming a global commodity. By sourcing it from countries with favorable electricity costs, H_2 procurement costs can be reduced.
- Hydrogen as a chemical energy carrier can be stored for longer periods without incurring losses. In conjunction with suitable storage systems (e.g., caverns), it is possible to decouple production and demand. This also includes seasonal storage and the creation of strategic reserves, comparable to today's fossil fuel storage practices.
- In the future, electrolysers and the use of an increasing renewable electricity supply from renewable sources should make it possible to largely produce hydrogen without emissions and in an economically-competitive manner.
- The use of electrolysers, as well as FCEVs and BEVs, offers the potential to optimize the power supply. By using these systems in a targeted manner, grid-serving operation is possible. Furthermore, waste heat from electrolysis can be integrated into heating systems and the oxygen can also be repurposed.
- Hydrogen can be used in different applications (e.g., electricity, heat, transport, and industrial processes). Hydrogen thus offers the potential for sector coupling desired by policymakers.

In the context of sustainable decarbonization, the way in which energy is procured for electric transportation is highly relevant. The prerequisite for zero-emission transportation is therefore that both the charging and production of H_2 take place using "surplus electricity" generated by renewable energy technologies that cannot be used for the general power supply. In a transitional phase, however, the use of so-called "gray" electricity or hydrogen should also be tolerated, provided that this can still contribute to a reduction in greenhouse gas emissions.

A rough estimate of the average annual consumption of BEVs with different energy demand and use, as well as pure AC charging (onboard charging systems) is shown in Table 4. With a share of 50 % BEVs in Germany (currently approximately 46,5 million registered passenger cars), about 52 TWh to 104 TWh of additional electricity consumption could be assumed. Generation would amount to about 56 TWh to 113 TWh.

With the use of FCEVs and the same level of market penetration, generation would amount to approximately 130 TWh to 260 TWh due to the 2,3 times greater energy demand (Figure 12). This means that, compared to 2017, which saw electricity generation of about 550 TWh, BEV generation would be expected to be 21 % higher, and FCEV generation about 50 % higher [77]. With a share of renewable electricity generation of 80 %, this corresponds to the expected electricity surplus of 220 TWh to 270 TWh (see the "Results of the scenario analyses" above).

Hydrogen procurement in every phase of market introduction to be assessed as uncritical in terms of availability and costs

Due to numerous climate-friendly production options, it should be possible to cost-effectively procure H_2 and in sufficient quantities at every stage of market introduction, mainly on the basis of domestic energy sources. Nevertheless, experience in Germany shows that there are currently problems with the supply of green hydrogen, both in sufficient quantities and at reasonable market prices.

Table 4. Need for additional electricity generation as a function of specific electricity consumption and mileages of BEVs

Vehicle consumption in kWh/100 km	Mileage per year in km	Annual consumption in kWh	BEVs in m	Electricity demand in TWh	Required additional annual electricity generation in TWh
15	15.000	2.250	23	51,75	56,25
20	15.000	3.000	23	69,00	75,00
25	15.000	3.750	23	86,25	93,75
30	15.000	4.500	23	103,50	112,50

In the short term, residual hydrogen from industrial processes and methane steam reforming can be used; in the medium to long term, renewable primary energy sources should be used for H_2 production. In the transitional phase, higher costs are to be expected compared to battery charging infrastructures, which will decrease significantly in due course due to better infrastructure utilization. The option of renewable electricity use is complementary to the expansion of renewable electricity generation, which requires efficient and cost-effective options for storage and use due to increasing amounts of electricity that cannot be used on the grid. Taking into account the necessary infrastructural components, it can be shown that H_2 costs at fueling stations are competitive with today's fuel costs (in each case, excluding taxes and levies). Studies on global H_2 logistics have shown that hydrogen can be produced cost-effectively in regions with an especially high volume of renewable energy sources and transported to the centers of consumption, e.g., by ship.

Hydrogen production via electrolysis reduces CO_2 emissions (Power2Hydrogen)

With respect to hydrogen, its production is one of the key issues. Over 95 % of today's hydrogen production is based on fossil fuels. About 90 % of the annual hydrogen demand of, currently, about 40 to 60 million t is needed for industrial applications. In this context, hydrogen is an indispensable chemical that serves as an energy carrier, additive or reducing agent. First and foremost, hydrogen is used as a basic chemical for the synthesis of ammonia and other fertilizers, such as urea, methanol, various polymers, and resins. Other major consumers in today's hydrogen industry are refineries, the metal industry, and also the semiconductor, glass, and food industries. The remaining 10 % is used in the energy sector and a vanishingly small percentage for the operation of fuel cell vehicles. This application in particular is considered a lucrative opportunity for the use of sustainably-produced hydrogen.

When assessing H_2 procurement costs, it must be taken into account that hydrogen is to be regarded as a globally-traded product. This means that it is possible to take advantage of favorable procurement opportunities in order to reduce energy costs. H_2 producers must therefore face competitors who can sometimes take advantage of highly favorable electricity prices. Examples include the purchase of hydrogen from Canada [78] or Norway.

Currently, H_2 production is primarily carried out via steam reforming, coal gasification and partial oxidation. On average, about 10 kg of CO_2 per kg of H_2 to 15 kg of CO_2 per kg of H_2 are produced (Figure 21), which are reintroduced into the material cycle and recycled, especially during the reforming process.

With regard to emission-free electric transportation, alternatives are needed for H_2 production. These exist in the form of biomass gasification and hydrogen electrolysis based on renewable energy.

The technology with the highest CO_2 reduction potential and, in the long term (2030), with the highest technical maturity level (TRL), is water electrolysis (Power2Hydrogen) [80]. With the help of an electric current, this technology converts water into hydrogen and oxygen without emitting CO_2. The prerequisite for this is the use of renewable electricity, which cannot be used for conventional needs. On the other hand, as Figure 21 shows, if H_2 is produced by electrolysis and the emissions of the power plant that provides the electricity for electrolysis is allocated, CO_2 emissions are expected to be significantly higher compared to reformation [79]. If renewable energy sources are used instead, there is a corresponding reduction in CO_2 emissions.

At present, the construction and commissioning of an electrolyser, regardless of size or location, is subject to a permit in accordance with the Federal Immission Control Act (BImSchG). It is complicated and costly, however. Due to the emissions of the plant (small amounts of oxygen and purified water), it is recommended to review the obligation to obtain a permit for electrolysers according to the BImSchG or to create an exemption for electrolysers. It would be conceivable to link an exemption to the installation site or the maximum amount of hydrogen that can be stored at the plant. This would then be a solution analogous to other gaseous fuels at fueling stations, which do not fall under BImSchG up to a storage quantity of 3 t.

The hydrogen production costs are defined by the investment costs for the electrolysers, but mainly by the electricity costs and operating time [81; 82]. Due to the high levels of investment required, hydrogen production cannot be made economical in the medium term using surplus electricity alone.

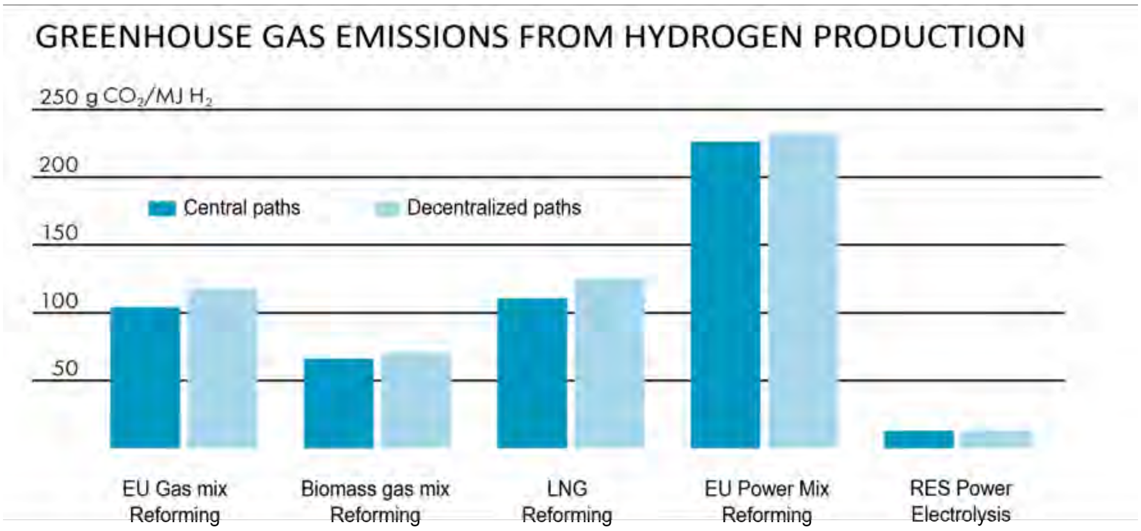

Figure 21. Specific greenhouse gas emissions from hydrogen production (source: Shell)

Figure 22 describes H_2 production costs using water electrolysis (assumptions: CAPEX of electrolysis of 450 USD/kW for large-scale water electrolysers, with, e.g., 400 MW WACC of 7 %, depreciation over 30 years, efficiency of 70 %). The production costs are only to be considered as reference values and are only valid under the premises outlined here, i.e., electricity procurement without grid costs and EEG levies, etc. The costs of electrolysis are not included in the calculation. Similarly, cost-increasing effects, e.g., special quality requirements for the purity of H_2, are not taken into account. The results show that from an operating time of approximately 4.000 hours per year, the hydrogen production costs are mainly determined by the electricity price. However, these 4.000 hours (i.e., almost six months of operation per year) cannot be achieved solely by exploiting RE generation peaks ("surplus electricity"). As investment costs continue to fall, the number of full-load hours required for economic operation will also continue to decrease.

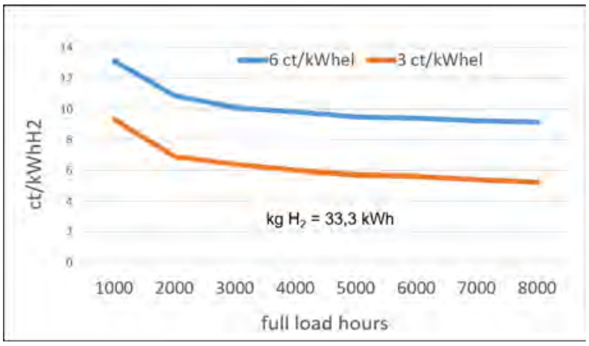

Figure 22. Hydrogen production costs as a function of the electrolyser's full load hours and electricity costs (source: inecs, based on [83])

The H_2 production costs of gasification processes are currently on the order of 2 €/kg ± 30 € ct) (corresponding to about 6 € ct/kWh related to the calorific value). The aim should be to achieve these values for H_2 from electrolysers as well. It must be taken into account here that hydrogen is to be regarded as a global trading product.

Use of hydrogen for seasonal energy balancing and to support sector-coupling

Hydrogen is an ideal energy storage medium for the challenges posed by the energy transition. It could be used in the power supply in the medium-term but also for seasonal energy balancing. During so-called "dark lulls" – periods of up to six weeks – in which there is no or only a small amount of wind and photovoltaic power, periods without significant RE power generation could be bridged by reconverting the hydrogen produced during periods featuring RE surpluses.

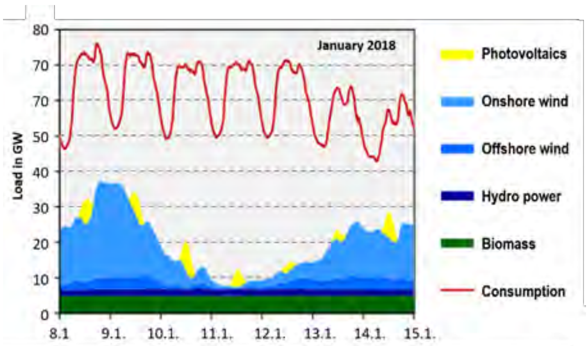

Figure 23. Feed-in from renewable energy and load profile in Germany (source: Bundesnetzagentur/SMARD.de)

Suitable storage facilities include salt caverns (hydrogen or methane), underground pore storage (methane), and also containers for liquids, whereby the hydrogen would be integrated into a storable carrier liquid.

The greatest economic benefit of Power2Hydrogen arises from so-called sector coupling. This describes the synergistic effects that arise from the use of electrolysis for the decarbonization of industry, transportation based on hydrogen and grid stabilization. Here, it is especially advantageous that through the chemical storage of electrical energy, hydrogen production for transportation can be decoupled in terms of time from demand (e.g., for transportation applications). This can lead to significant savings in the expansion of infrastructure on the electricity side. However, this is opposed by the expansion of the hydrogen infrastructure (see Section 4.3 “Investment costs for H_2 infrastructure similar to those for BEV supply”).

Electric transportation modules enable grid-serving operation

Water electrolysis and battery storage systems offer the potential to be used advantageously in terms of power supply. The following areas of application are conceivable:

Due to its flexible mode of operation, water electrolysis offers the potential to integrate a steadily increasing share of renewable energy into the electricity grid. Load peaks caused by the excessive production of wind and solar energy can thus be absorbed and do not have to be regulated. In 2015 and 2016 alone, 4,7 TWh (2015) and 3,7 TWh (2016), respectively, had to be interrupted in Germany. In 2016, this resulted in a compensation payment of around €370 million EUR [85]. Electrolysis could also offer the potential to save some of the costs incurred through re-dispatch and feed-in management.[1)] In 2017 alone, these amounted to €1,4 billion [86]. As the majority of the RE curtailments were caused by currently existing grid bottlenecks, electrolysers would therefore need to be installed “before” the grid bottleneck point. The problem of the low operating and full-load hours for the required electrolysers, which can still be expected in the medium term, was already outlined above.

The targeted control of electrolysers offers options for balancing the energy market. As these systems can be quickly regulated or switched on and off as needed, they could be used in the sense of balancing the market [87].

Vehicle batteries lend themselves to grid load optimization in distribution grids. Through controlled charging, it could be possible to achieve better utilization of the affected grid areas; by reducing the charging power, grid overloads in the local grid areas could be avoided and bottlenecks in upstream grid parts compensated for by feeding in power from the battery (vehicle-to-grid). Applications for the provision of reactive power are also conceivable.

Applications for FCEVs include domestic energy supply [88]. By connecting the system to the household energy supply after reaching the residential building, it can be used as a supplement to the electricity supply, and so electricity consumption from the public grid can be reduced. As the average power demand of a household does not usually exceed 1 kW and the power of the fuel cell is estimated to be around 50 kW, a full supply could even be possible for a time in an emergency.

4.5 Critical raw materials

Core statements

- Diversification of (elecxtric transport) technologies reduces the risk of raw material shortages.
- Critical raw materials include lithium, nickel and cobalt for batteries and platinum for fuel cells, with a declining trend. The production capacities of these materials must be expanded, preferably by increasing the recycling rate.

Is a (r)evolution towards electric transportation even possible from a raw materials perspective? This question will be examined below from a global and long-term perspective.

Raw materials are needed for any technology market penetration, and also for maintenance. These come either from primary sources such as ore mining or, usually with a time lag, (also) from secondary sources, such as recycling. Here, a mismatch between supply and demand can occur, whereby a distinction is made

1) Adjustment of the power feed-in of power plants by the transmission system operator in order to avoid regional overloads of individual resources in the transmission system.

between absolute, temporary and structural shortages. While the development of new production sources and their substitutions have so far prevented an absolute shortage of a raw materials, temporary shortages have already occurred, e.g., a few years ago for rare earth metals, largely caused by China's monopolistic position. Structural shortages usually occur when demand does not lead to direct extraction; this is especially true for so-called secondary metals, whose production volume depends only on primary metals. This distinction is ultimately purely economic though [89; 90].

Specifically in terms of electric transportation, this paper primarily refers to a study commissioned by Agora Verkehrswende [91]. This in turn is essentially based on studies by the International Energy Agency (IEA) [92] on current and future vehicle sales figures, as well as on a U.S. Geological Survey (USGS) study [93] on current raw material extraction quantities and reserves, i.e., quantities and resources that can currently be economically extracted, i.e., known deposits. In short, a transportation scenario is considered that achieves the minimum target of the Paris Climate Agreement to limit the global and average temperature increase to (significantly) below 2 °C above pre-industrial levels. All road vehicles (cars, trucks, buses, motorcycles, e-bikes) are considered, with a focus on cars with a raw material demand share of over 80 % [91]. Furthermore, a globally growing vehicle sales market is assumed, which will roughly double to 131 million by 2030 (Figure 24) [92]. In addition to electric transportation, the demand for all other applications (steel, ceramics, jewelry, etc.) is also forecast and taken into account.

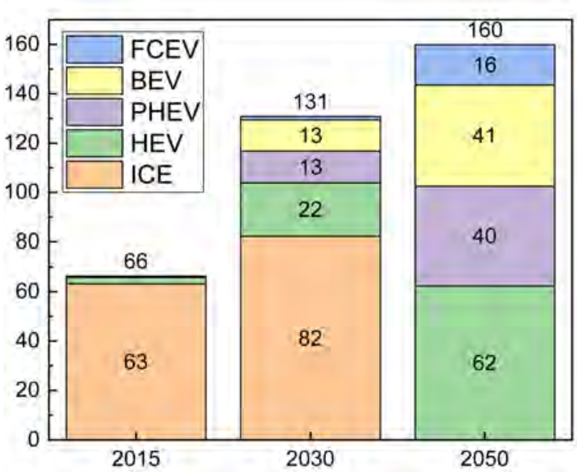

Figure 24. Annual passenger car sales figures (in millions of vehicles) for 2015, 2030, and 2050 for different vehicle types with electric drivetrains (source: University of Hanover, based on [92])

Similarly, battery capacities to increase the range for BEV passenger cars also increased from 30 kWh lithium nickel manganese cobalt oxides (NMC111) in 2015 to 50 kWh (NMC622) in subsequent sample years. Constant battery capacities were also assumed for the other drive types: HEVs with 1 kWh, PHEVs with 10 kWh, and FCEVs with 2 kWh [91].

Taking into account the current state of the art and foreseeable developments, rare earth metals for the electric motor, lithium (Li), cobalt (Co), nickel (Ni), and graphite for the battery, as well as platinum (Pt) for the fuel cell, have been identified as critical raw materials for electric transportation [91]. Today, only graphite can already be produced from synthetic sources. Although synthetically-produced graphite is more expensive than its natural counterpart, it is of higher quality. Consequently, the availability of graphite as a raw material is not critical [91].

Synchronous motors that make use of neodymium-iron-boron magnets are mostly used in electric motors, which consist of ~30 % mass of rare earth metals such as neodymium, dysprosium, and terbium, which have a comparatively high coercive field strength and heat resistance [94]. In the production of rare earth metals, the People's Republic of China is the main supplier with a monopoly-like share of over 90 % [93], which in turn has already led to temporary shortages and major price fluctuations [91]. This is undergirded by an extremely low recycling rate of only 10 % [95]. In contrast, there are already successfully-implemented developments of new magnets with a complete substitution of dysprosium and terbium, as well as a reduction of neodymium by less critical rare earth metals such as lanthanum and cerium by up to 50 % [96]. Furthermore, a complete substitution of rare earth metals in asynchronous motors and electrically-excited synchronous motors in electric cars has already been successfully demonstrated [97; 98].

For all of the other critical raw materials mentioned above, the production capacities from primary and secondary sources, as well as the respective demand for the reference year 2015 and projected reference years 2030 and 2050 are summarized in Figure 25.

What all raw materials have in common is that the current production volumes cannot cover projected demand. Whereas the production volumes for nickel and platinum will have to be roughly doubled in the long term, the projected volumes for lithium and cobalt already correspond to an increase by a factor of 17 and 6, respectively. The increasingly predominant battery demand is largely responsible for this.

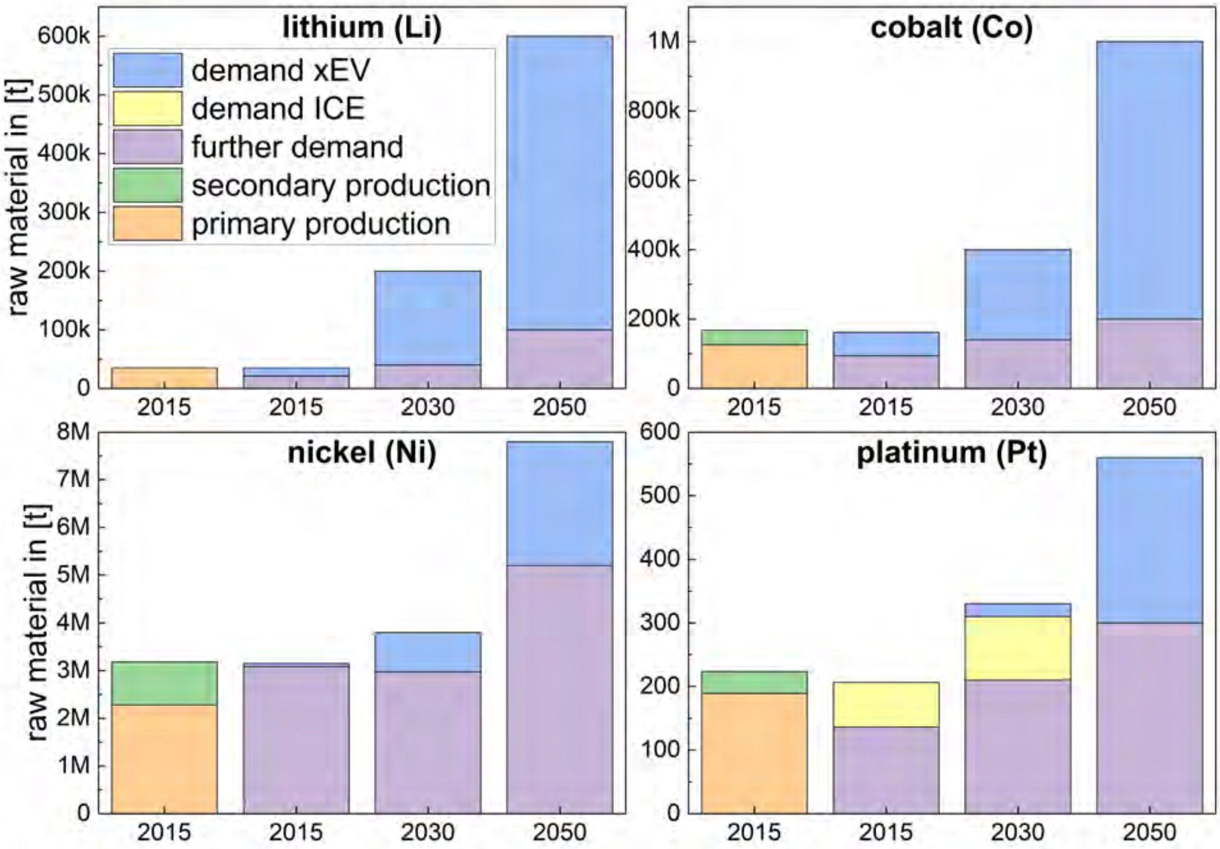

Figure 25. Primary and secondary production and demand (ICE, xEV, and other applications) of Li, Co, Ni, and Pt in 2015, 2030, and 2050 (projections for demand only) (source: University of Hannover)

For lithium in particular, the situation is aggravated by the fact that there is currently no de facto recycling for economic reasons and that extraction is concentrated in Australia, Chile, and Argentina, which maintain a market share of around 90 % [89; 93].

Cobalt is extracted ~98 % as a secondary metal in nickel and copper mining, with more than half of the mine production coming from the Democratic Republic of the Congo under somewhat inhumane production conditions [93]. These two factors tend to create a higher risk of structural and temporary shortages, which seem to already be reflected in a significant price increase from €50/kg to €75/kg over the last six months [99]. In contrast to lithium, the recycling rate for cobalt is already at a relatively high level of over 50 % [95].

Currently, nickel demand for battery applications plays only a minor role compared to the predominant stainless steel sector. A fairly broad, global distribution in terms of primary production and raw material reserves, as well as a recycling rate of over 50 % already achieved, also has a positive effect on the supply-demand situation [91; 93; 95].

Interestingly, the availability of platinum or platinum group metals (PGMs), including palladium and rhodium, is usually only discussed in connection with fuel cells, but not with internal combustion engines (ICEs). However, around 5 g of PGMs (6 % Pt, 89 % Pd, and 6 % Rh) are used in exhaust gas treatment in a petrol car and around 10 g of PGMs (74 % Pt, 22 % Pd, 4 % Rh) in a diesel car [100]. In contrast, “only” 10 g to 20 g of platinum (Pt or Pt alloys) per vehicle are used as electrocatalysts in the pre-series and small-series fuel cell cars available today, with a downward trend [52; 101]. The concentration of both primary production and raw material reserves of platinum (and other PGMs) in South Africa (~70 % and ~90 %, respectively) can be seen as disadvantageous and risky [93]. However, this monopolistic position is mitigated by a very high recycling rate of over 50 % [95].

Thus far, the focus of this summary has been on production and demand quantities and will now be supplemented by the respective raw material reserves and resources. Figure 26 shows the projected demand quantities for all applications, including (electric) transportation, cumulatively up to the year 2050 compared to the raw material reserves and resources in the reference year 2016. It can be seen that new raw material reserves must be developed, especially for cobalt and nickel, in order to prevent shortages.

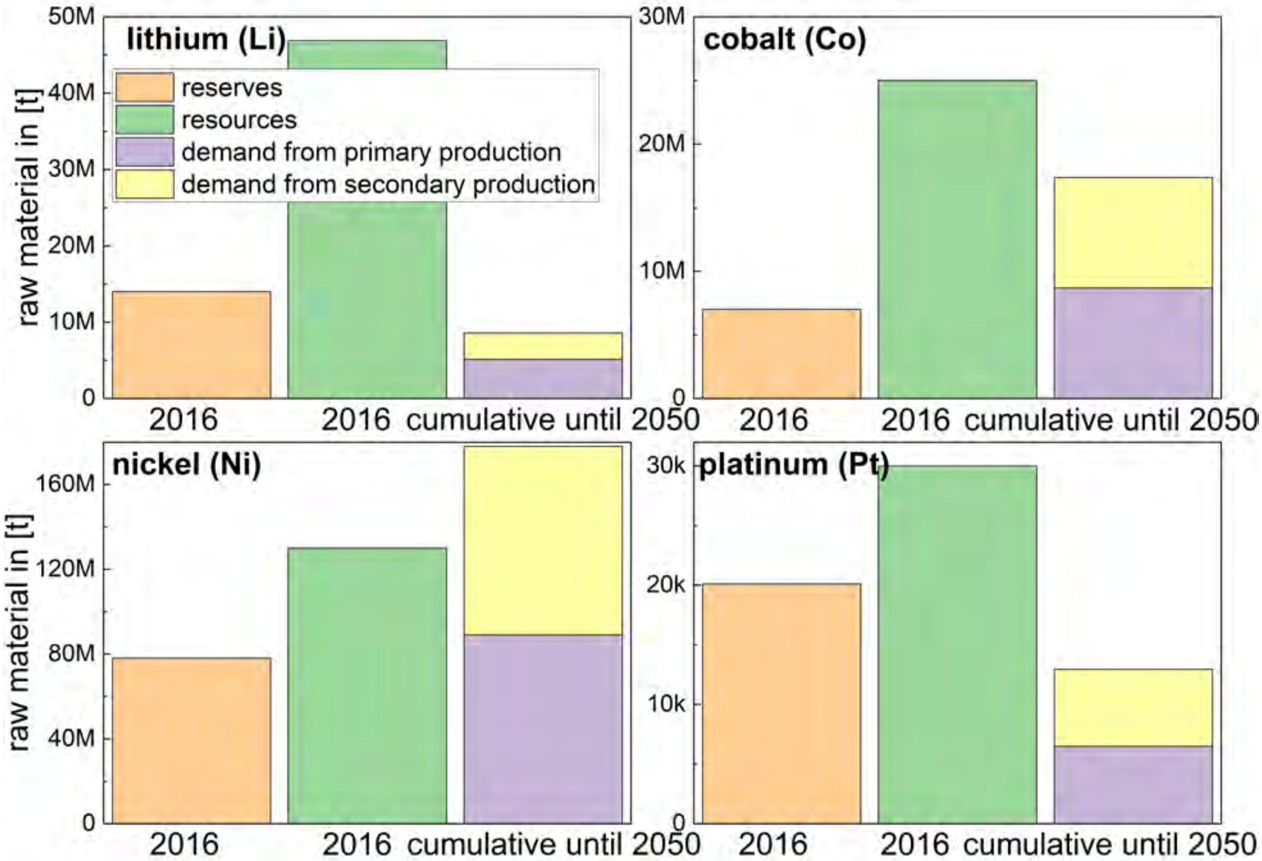

Figure 26. Raw material-specific reserves and resources (2016, according to [93]) and cumulative demand for all applications including electric transportation until 2050a (source: University of Hannover)

a) Derived from [91] with current recycling rates for Co, Ni and Pt of 50 % each [95] and estimated future recycling rates for Li of 40 % [91].

As a small digression, hydrogen production by means of water electrolysis must also be mentioned at this point. While alkaline and high-temperature electrolysers can function without PGMs as electrocatalysts, iridium and platinum are used in the PEM variant. Iridium is mined exclusively as a secondary metal at approximately 4 t per year [89] plus products from recycling (the Ir recycling rate is 25 % to 50 %) [95]. Although there have been no known shortages thus far, this could change, taking into account primary production and the current state of the art, as soon as annual new installations of PEM electrolysers grow from the current double-digit MW range to the single-digit GW range [102; 103]. In order to avoid shortages in the long term, the recycling rate should therefore be further increased, the catalyst loading further reduced and, ultimately, iridium substitution pursued.

4.6 Car costs (TCO)

Core statements

- The cost of using BEVs and FCEVs as passenger cars is currently predominated by acquisition costs.
- The series production of battery systems is more advanced than that of fuel cells. Accordingly, the cost reduction for battery systems is currently much more pronounced than for fuel cell systems.
- With higher energy or range requirements, FCEVs have cost advantages over BEVs. This effect increases with the start of series production. .

A rough comparison of the usage costs for the Toyota Mirai, Tesla Model S 75 and Nissan Leaf vehicles in Table 5 shows the high current influence of investment costs. The acquisition costs noted here refer to Table 1, and the consumption data correspond to the new European driving cycle (NEDC). Under simplifying assumptions that the vehicle depreciates over 10 years and drives 100.000 km during this time without battery or fuel cell replacement, annual costs of between €3.620 and €8.580 result for a mileage of 10.000 km per year. As the table also shows, with more favorable acquisition costs for the Toyota Mirai and the energy costs assumed here, cost parity with the Tesla S 75 could already be assumed today.

For the energy costs of the Toyota Mirai, a relatively high value of 9,5 €/kgH_2 (0,285 €/kWh) was assumed in the comparative calculation. It corresponds to the currently existing purchase conditions of the NRW Energy Agency for refueling at the H_2 fueling stations. As is shown in Section 4.4, H_2 production costs for gasification processes amount to only €2/kg ± 30 €/ct. Even taking into account trade margins, this should allow for a more favorable energy price for FCEVs in the case of a broader market introduction.

However, it must be taken into account that the H_2 price given in Table 5 does not include taxes and duties other than VAT. The question of the extent to which this approach is justified, even if this technology becomes more widespread, must remain open in the context of this study.

The electricity price mentioned, on the other hand, roughly corresponds to the current price for household customers and includes all taxes and levies.

Cost development

Estimates show that production costs for FCEVs are lower than those for BEVs once a significant number of units are produced. The costs for battery systems have fallen from €600/kWh in 2010 to approximately €200/kWh at present. Thanks to mass production, cell prices are thus approaching material prices [104] (Figure 27).

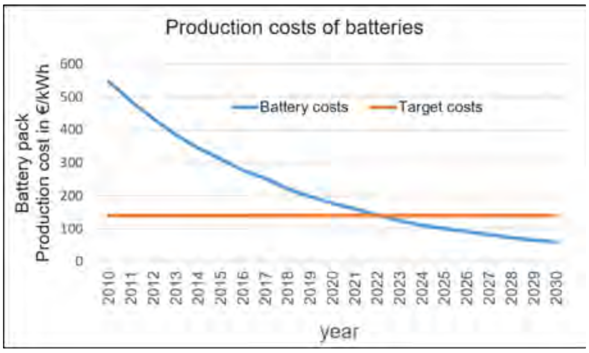

Figure 27. Manufacturing costs of BEVs (source: inecs, based on [105])

Note

Recent information from the industry – not backed up by sources – suggests that the cell prices of battery costs are already well below €200/kWh today. This would benefit an accelerated market introduction.

Table 5. Comparison of annual costs of FCEVs and BEVs (source: Fraunhofer ISE).

	Acquisition in €	Depreciation (10 years) in €	Energy costs in €/kWh	Consumption in kWh per 100 km	Energy costs (10.000 km) in €	Costs per year in €
Toyota Mirai	78.600	7.860	0,285 (H_2)	25.308 (H_2)	722	8.582
Toyota Mirai (price reduced)	71.999	7.200	0,285 (H_2)	25.308 (H_2)	722	7.922
Tesla S 75	71.999	7.200	0,296 (el.)	18.500 (el.)	548	7.748
Nissan Leaf	31.950	3.195	0,296 (el.)	14.600 (el.)	432	3.627

According to a USDOE analysis, the cost of fuel cell systems will fall to USD $47/kW by 2020, assuming a unit size of 80 kW and production volume of 100.000 units per year [106]. For the type IV hydrogen tank – consisting of an inner plastic bladder (liner) for gas tightness with composite wrapping to take the load from the internal pressure – designed for 700 bar with a capacity of 5,6 kg (corresponding to about 185 kWh), another study estimates less than $16/kWh (i.e., about $3.000 for this hydrogen tank) [107].

Assuming identical BEV and FCEV costs for the converter and electric motor components, the cost of the battery system can be compared to that of the hydrogen system. An 80 kW propulsion system with a 5,6 kg hydrogen storage tank would cost €6.744 (US DOE) or 8.000 EUR for a production of 100.000 units per year, and the vehicle would have a range of at least 500 km. An equivalent battery system (comparable range) would require a battery capacity of about 100 kWh at a consumption of 20 kWh/100 km and cost about €20.000, assuming a battery cost of €200/kWh. With a range of 200 km, both drivetrains would have the same costs.

Note

Information from the industry supports these estimates. According to this, cost parity between BEVs and FCEVs can be assumed from mid-2020. This also applies under the assumption that battery costs will continue to decrease. For high-floor vehicles such as SUVs, cost parity would already be reached at lower ranges due to the higher specific energy demand per km and the larger batteries required for this. For flat-bottomed vehicles (e.g., coupés), cost parity can be assumed to be reached later due to the smaller batteries in the vehicle. This supports the statement that BEVs would be more advantageous, especially for short-distance traffic in conurbations, whereas FCEVs are better for long-distance travel.

The available database is currently insufficient for a comprehensive, reliable and comparable lifecycle analysis that takes into account emissions or abiotic environmental factors in addition to costs. Energy consumption, CO_2 emissions [108] and costs for the production of Li-ion batteries have been compiled in various publications, but little has been published on recycling. As the assumptions within the studies differ greatly in some cases, a comparison is not provided.

5 Research needs

The analyses outlined within the framework of this study show that there is not yet sufficient information available on various questions, or that the information that is available is inconsistent in some cases. This suggests a need for further research on the following topics:

- **Peripherals and powertrains:** BEVs, as well as FCEVs have, in addition to the powertrain, a large number of ancillary components and systems (e.g., valves, pumps) that are still custom-made and on which little information is available. This also includes the production of electro-technical components such as converters and electric motors for electric drivetrains. Further analytical activities could clarify this.

- **Battery:** The production of Li-ion batteries is relatively costly and the ecological advantage relativized when the emissions generated in the production of the battery are taken into account. However, recycling of the battery and technological advances – e.g., the use of renewable energy sources in production – are not yet taken into account. The data situation is also incomplete, and so existing statements are not certain. Further studies to verify the data are thus recommended.

- **Service life:** The information on the service life of BEVs and FCEVs is not yet consistent in some cases. There is therefore a need for further research and practical experience.

- **Lifecycle analysis:** Several large studies have already been conducted to analyze the lifecycle or corresponding operating costs of BEVs or FCEVs, which were evaluated in the context of this study [1; 109; 110]. The analysis of the studies demonstrated that the focus of the studies was mostly on the comparison of BEVs or FCEVs with conventional drivetrain vehicles. A direct comparison of the two technologies has rarely been made. In addition, the studies arrive at quantitatively and qualitatively different results for the important parameters, e.g., the determination of greenhouse gas emissions and abiotic depletion, and above all for operating costs. This is primarily due to the use of different databases, which are an important building block for carrying out a lifecycle analysis. For a meaningful comparison of the studies, the assumptions made and databases used in the studies would need to be aligned. It can therefore be concluded that no well-founded comparison can be made on the basis of the existing analyses and that there is a need for further research here.

- **Cost reduction:** Due to the still existing optimization potential and still low numbers of units, there is a need for additional research, for example in the areas of material selection, production technologies, and catalyst loading (platinum for FCEVs and Co for BEVs) with respect to efficient cost reduction with scaling effects.

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VDI – The Association of German Engineers
Technology and Society
Dr.-Ing. Eleni Konstantinidou
Phone +49 211 6214-219
geu@vdi.de
www.vdi.de

VDE Association for Electrical, Electronic &
Information Technologies
Dr.-Ing. Thomas Benz
Phone +49 69 6308-346
etg@vde.com
www.vde.com/etg