SHELL HYDROGEN STUDY

ENERGY OF THE FUTURE?

Sustainable Mobility through Fuel Cells and \( \text{H}_2 \)

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INTRODUCTION

Over the years Shell has produced a number of scenario studies on key energy issues. These have included studies on important energy consumption sectors such as passenger cars and commercial vehicles (lorries and buses) and the supply of energy and heat to private households, as well as studies on the state and prospects for individual energy sources and fuels, including biofuels, natural gas and liquefied petroleum gas.

Shell has been involved in hydrogen production as well as in research, development and application for decades, with a dedicated business unit, Shell Hydrogen. Now, in cooperation with the Wuppertal Institute in Germany, Shell has conducted a study on hydrogen as a future energy source.

The study looks at the current state of hydrogen supply path- ways and hydrogen application technologies and explores the potential and prospects for hydrogen as an energy source in the global energy system of tomorrow. The study focuses on the use of hydrogen in road transport and specifically in fuel cell electric vehicles (FCEVs), but it also examines non-automotive resp. stationary applications.

RESEARCH OBJECTIVES AND KEY QUESTIONS

Shell scenario studies present facts, trends and prospects on specific key energy issues in a compact form. As in the previous Shell studies on passenger cars, commercial vehicles, domestic heating and individual energy sources and fuels, the initial focus is on providing an expert analysis and assessment of a subject.

There has certainly been plenty of discussion and reporting on hydrogen, and it is an exceptionally simple element. At the same time, however, hydrogen is not a familiar product, especially among end users who are accustomed to petrol and electricity. So far, any experience of hydrogen is largely limited to its use as a feed material in chemical production and as a technical gas in industry. For that reason one of the most important aims of the Shell Hydrogen Study is to provide basic information about the element and about the use of hydrogen as an energy source. The first purpose of the study is to give an overview of the special properties and advantages of hydrogen.

Hydrogen is one of the ten most common elements on the surface of the Earth that is accessible to man. In nature, however, it does not exist in pure form, but rather only as part of a compound. If hydrogen is to be used as an energy source in a future hydrogen economy, then first of all, its origin needs to be clarified. Where does hydrogen occur? From which materials and how can it be produced, and using what technical processes? If a future energy economy is to be sustainable, the way in which it is generated is key. So what are the advantages and disadvantages of the various hydrogen supply pathways?

Highly developed energy systems rely increasingly on electricity as a secondary energy source. Electricity has many advantages as an energy source, but some disadvantages too: it can generally only be directly stored in small amounts and for short periods of time, and its transportation is mostly grid-based. Chemical energy storage via hydrogen could represent an alternative or an important supplement to existing energy stores. If hydrogen is to play a part in the energy system of the future, the possibilities for storing and trans- porting hydrogen need to be analysed.

In the past, debate about the use of hydro- gen has centred above all on automobility. But hydrogen usage cannot be and is not limited to transport applications. In new technologies there are often synergies between different applications, and these need to be taken into account when looking at learning curves and economies of scale of (new) technologies. And when it comes to the use of scarce resources (like energy and fuel), competing uses need to be considered. This raises the following question: What (other) fundamental application areas – as a material and an energy source – are there for hydrogen? And, with regard to energy applications:

What are the main conversion methods involved in using hydrogen for energy purposes? Alongside the mobility applications for hydrogen technology, are there any stationary applications for hydrogen as a source of energy?

The focus of this study is the issue of sustainable mobility through fuel cells and hydrogen (H2). When we think of hydrogen and mobility, fuel cell electric vehicles, in particular passenger cars, are what come to mind. But hydrogen and fuel cells can be used by other means of transport too. Therefore, the aim of this study is to give an overview of the technical state of and prospects for hydrogen and fuel cell technology in all transport sectors, including non-road means of transport.

After assessing the technological maturity of motor vehicles and passenger cars in particular, we look at the costs and cost-effectiveness of hydrogen mobility as an important decision-making criterion, as well as the development of a hydrogen supply infrastructure. Finally, since hydrogen-powered vehicles are only viable if they can be operated more sustainably than today’s vehicles, we use scenario techniques to estimate and assess possible energy and environmental balances for future fuel cell passenger car fleets.

AUTHORS AND SOURCES

Shell worked closely with the German research institute and Thinktank Wuppertal Institute to produce the Shell Hydrogen Study. Back in 2007 the Wuppertal Institute examined and evaluated the concept of “geological CO2 storage” as a possible climate policy action for Shell (WI 2007). The Wuppertal Institute researches and develops models, strategies and instruments for transitions to sustainable development. Its work centres on the way in which challenges in terms of resources, climate and energy use and influence are assessed by the economy and society. The Future Energy and Mobility Structures research group, which was involved in the study, is concerned in particular with the transition to sustainable structures from a technical / structural and systems analytical point of view.

The project leader and coordinator of the Shell Hydrogen Study on behalf of Shell was Dr. Jürgen Louis. The scientific coordina- tor on behalf of the Wuppertal Institute was Dr. Karin Arnold. She was supported by Andreas Pastewko and Gertrau Schiwer. The work was carried out under the scientific supervision of Professor Manfred Fischbeck.

The following authors at Shell also con- tributed to the scientific preparation of the study: Dr. Jürgen Louis, regarding technical and scientific questions about hydrogen and fuel cell technology, Uwe Schabla, regarding stationary fuel cell applications, and Dr. Christoph B. Babar, regarding the preparation of energy and greenhouse gas balances and scenario techniques.

In addition, many other experts, decision makers and stakeholders from science, busi- ness and politics were consulted during the preparation of the Shell Hydrogen Study. Shell would like to take this opportunity to thank all concerned for their contribution and cooperation. A selection of relevant data and sources can be found at the end of the study.

ENERGY OF THE FUTURE?

Shell Hydrogen Study
1.1 WHAT IS HYDROGEN?

The name “hydro-gène” (“water producer”) was first coined in 1787 by the French chemist Antoine Laurent de Lavoisier, from the Greek words “hydor” (water) and “genes” (producing). It had earlier been called “inflammable air” by the English chemist and physicist Henry Cavendish because of its high flammability. The German name “Wasserstoff” (“water substance”) likewise refers to its water producing properties.

Hydrogen (chemical symbol H for the Latin name hydrogenium) is the first element in the periodic table and also the simplest. Ordinary hydrogen consists of a positively charged nucleus (proton) and a negatively charged electron. Hydrogen has the lowest atomic weight of any element at 1.008 grams per mol (g/mol); hydrogen has the lowest atomic weight of any element, at 1.008 grams per mol (g/mol); atomic hydrogen is 12 times lighter than carbon (C), 14 times lighter than nitrogen (N) and 16 times lighter than oxygen (O).

In addition to ordinary or light hydrogen 1H (protium), there are also two other hydrogen atoms (isotopes): heavy hydrogen (2H) or deuterium (D) and super-heavy hydrogen (3H) or tritium (T), with additional neutrons. As the neutron in the hydrogen nucleus is roughly the same weight as the proton, deuterium is approximately 12 times lighter than carbon (C), 14 times lighter than nitrogen (N) and 16 times lighter than oxygen (O). In addition to ordinary or light hydrogen 1H (protium), there are also two other hydrogen atoms (isotopes): heavy hydrogen (2H) or deuterium (D) and super-heavy hydrogen (3H) or tritium (T), with additional neutrons. As the neutron in the hydrogen nucleus is roughly the same weight as the proton, deuterium is approximately twice as heavy and tritium approximately three times as heavy as proton. Almost all hydrogen (99.985 %) is ordinary hydrogen, only 0.015 % occurs as heavy hydrogen. The proportion of super-heavy hydrogen is vanishingly small.

Under standard conditions, i.e. ambient temperature and atmospheric pressure of 1.013 bar, atomic hydrogen (H) does not occur. Instead, hydrogen exists in dimerised form, where two hydrogen atoms firmly combine to form a hydrogen molecule (H₂). The molecular weight of a hydrogen molecule is then 2.016 g/mol.

1.2 WHERE DOES HYDROGEN OCCUR?

Hydrogen is the first and most important element in the universe. Its estimated mass fraction is in the order of 75 %. In the early universe, some 13.8 billion years ago, hydrogen nuclei were formed by fusion at extremely high temperatures (nucleosynthesis). In the hot interior of stars, the subsequent stellar fusion of hydrogen to helium, also known as “hydrogen burning”, is the most important and robust source of energy in their life cycle. The age of a star can be determined from the distribution of the elements and the stellar mass.

Space is filled with highly diluted hydrogen and also contains gigantic gas clouds consisting of hydrogen. The sun, which is around 4.6 billion years old, is a so-called main sequence star, which releases its radiant energy from hydrogen burning. Hydrogen is also the most frequently occurring chemical element on the giant gas planets (Jupiter, Saturn) of our solar system.

Unlike in outer space, the proportion of hydrogen in the elements on Earth is much smaller. The part of the Earth that is accessible to humans makes up less than 1% of the Earth’s mass. In the region of the Earth’s crust, oceans and atmosphere, the mass fraction of hydrogen is just 0.9 % (Mariner/Müller 2010). The proportion of hydrogen in the Earth’s atmosphere is only 0.03 parts per million (ppm).

Furthermore, hydrogen on Earth exists only rarely in its pure form, in most cases it is found in chemically bonded form. The largest proportion of hydrogen on Earth occurs as a compound with oxygen, in the form of water or water vapour. Corresponding to the relative atomic masses of hydrogen and oxygen, water (H₂O) consists of approximately 11.18 percent by weight hydrogen; in other words, the mass ratio of hydrogen to oxygen is around 1:8.

Moreover, hydrogen occurs in almost all organic compounds. It is not only living creatures that are composed of organic compounds. Fossil energy sources also consist primarily of carbon-hydrogen compounds. For example, the hydrocarbon methane, the main constituent of natural gas, is made up of one carbon atom and four hydrogen atoms (CH₄). By contrast, in higher alkanes such as petrol and diesel fuel the carbon-hydrogen ratio is around 1:2, and in coal it is only around 1:1.
Almost since its discovery, hydrogen has played an important part in contemporary visions of the future, especially in relation to the energy industry and locomotion.

As early as 1874, the French science fiction writer Jules Verne (1828 – 1905) in his novel “L’Île mystérieuse” (The Mysterious Island) saw hydrogen and oxygen as the energy sources of the future. In his vision, hydrogen would be obtained by the breaking down of water (via electrolysis). Water, resp. hydrogen, would replace coal, which at the time was the dominant energy source in the energy supply industry.

In the 1960s, the successful use of hydrogen as a rocket propellant and of fuel cells to operate auxiliary power units in space – especially in the context of the US Saturn/Apollo space travel programme – provided further impetus to the fantasies surrounding hydrogen. Also in the 1960s, first passenger cars were fitted with fuel cells as basic prototypes resp. technology demonstrators.

During the 1970s, under the impression of dwindling and even more expensive fossil fuels, the concept of a (solar) hydrogen economy was developed, with H2 as the central energy carrier. Since the 1990s, hydrogen and fuel cells have made huge technical progress in the mobility sector. After the turn of the century, not least against the background of renewed global raw material shortages and increasingly urgent questions of sustainability, the prospects for a hydrogen economy were considered once again (Rifkin 2002).

More recently, the focus has increasingly been on hydrogen’s role in a national and global energy transition. Within this context, the value added of hydrogen (from renewable energies via electrolysis) in an increasingly electrified energy world has also been subject to discussion. Nevertheless, an important role is envisaged for hydrogen – especially as a clean, storable and transportable energy store – in an electricity-based energy future (Nitsch 2003; Ball/Wietschel 2009).

### 1.3 PROPERTIES OF HYDROGEN

Under normal or standard conditions, hydrogen is a colourless and odourless gas. Hydrogen is non-toxic and is not causing environmental damage – in that respect it is environmentally neutral.

In terms of the properties of substances, a distinction is made between physical and chemical properties. Physical properties are determined by measurement and experimentation, while chemical properties are observed by means of chemical reactions. One of the most important chemical properties of energy sources is the behaviour of the substance when it is burned (oxidation behaviour), either in a homogenous combustion process or by cold electrochemical combustion. Physical and chemical properties of substances influence both the use and usefulness of a substance and the way in which it is handled; that applies in particular also to the safe handling and storage of energy sources such as hydrogen.

#### PHYSICAL PROPERTIES

Hydrogen – by which both here and below we mean dihydrogen or equilibrium hydrogen mixtures (H2) – exists in gaseous form under normal conditions. For a long time hydrogen was believed to be a permanent gas, which cannot be converted into either of the other two states of aggregation, i.e. liquid or solid (Hollemann/Wiberg 2007).

In fact its boiling point is very low, at −252.76°C; this is close to the absolute zero temperature of −273.15°C and corresponds to 20.3 Kelvin (K) on the absolute temperature scale. Below this temperature hydrogen is liquid under normal pressure of 1.013 bar, above this point it is gaseous.

The state of aggregation is dependent not only on temperature, however, but also on pressure. Gases can thus also be liquefied by raising the pressure. However, there is a critical temperature above which a gas can no longer be liquefied, no matter how high the pressure. In the case of hydrogen the critical temperature is −239.96°C (33.15 K). If hydrogen is to be liquefied, its temperature must be below this point.

Similarly, once it reaches a sufficiently high pressure, a gas can no longer be liquefied, even by lowering the temperature further. This pressure is known as the critical pressure, and for hydrogen it is 13.1 bar.

#### The critical point

The critical temperature and critical pressure characterize the critical point of a substance. For hydrogen the critical point is approximately −240°C or 33.15 K and 13 bar. At the critical point a substance the liquid and gas phase merge. At the same time the critical point marks the upper end of the vapour-pressure curve in the pressure-temperature phase diagram. The critical density at this critical point is 31 grams per litre (g/l).

The melting point, at which H2 changes from the liquid to the solid state of aggregation, is −259.16°C or 13.9 K under normal pressure and is thus slightly lower again than the boiling point. This means that only the noble gas helium has lower boiling and melting points than hydrogen.

The triple or three phase point of a substance is the point in the phase diagram at which all three states of aggregation are in thermodynamic equilibrium; for hydrogen this point is at −259.16°C and 0.077 bar. The triple point is also the lowest point of the vapour-pressure curve. The vapour-pressure curve indicates pressure-temperature combinations at which the gas and liquid phases of hydrogen are in equilibrium. To the left of the vapour-pressure curve hydrogen is liquid, to the right it is gaseous. To the right of and above the critical point, hydrogen becomes a supercritical fluid, which is neither gaseous nor liquid. Compared with that of methane, the vapour-pressure curve of hydrogen is very steep and short – over a small temperature and pressure range. As a consequence, liquefaction takes place primarily by cooling and less so by compression. By contrast, the compressed storage of hydrogen (at 350 or 700 bar) always takes place as a supercritical fluid.

In connection with temperature and pressure changes, a special feature of hydrogen that has to be taken into consideration is its negative Joule-Thomson coefficient: when air expands under normal conditions, it cools down – an effect which is used in the liquefaction of gases, specifically in the Hampson-Linde cycle for the cryocooling of gases. Hydrogen behaves quite differently: it heats up when it is throttled. Only below its inversion temperature of 202 K (approx. −71°C) does hydrogen demonstrate a “normal” Joule-Thomson effect. By contrast, for the main constituents of air, nitrogen and oxygen, the inversion temperature is 621 K and 764 K, respectively.

Density is a physical quantity that is defined by the ratio of mass per volume. Gases have a very low density in comparison to liquids. A typical value for hydrogen gas is 0.089 kg/m³ (at 0°C and 1 bar).
comparison to liquid and solid substances. At a temperature of 0°C or 273.15 K, the density of hydrogen in its gaseous state is 0.089 grams per litre (g/l). Since air is around 14 times heavier than gaseous hydrogen, with a density of 1.29 g/l, hydrogen has a high buoyancy in the atmosphere. Hydrogen volatilises quickly in the open air.

Liquefaction plays an important part in the storage and transport of hydrogen as an energy source. In the liquid state at the boiling point, at -253°C (13.9 K) and 1.013 bar, hydrogen has a density of 70.79 g/l. At the melting point, at -259.2°C (13.9 K) and 1.013 bar, its density is 76.3 g/l (Hollemann/Wiberg 2007).

Liquefaction increases the density of hydrogen by a factor of around 800, and the storage volume falls correspondingly. For the purposes of comparison, when liquefied Petroleum Gas (LPG) is liquefied, the density or volume factor, depending on the proportion of butane/propane, is around 250, when methane is liquefied to form Liquefied Natural Gas (LNG), the factor is around 600 (Shell 2013, 2015).

Another relevant feature of hydrogen is its extremely high diffusibility. As the lightest gas, hydrogen can diffuse into another medium, passing through porous material or even metals (Hollemann/Wiberg 2007). This can also cause materials to become brittle. In storage, the high diffusivity requires the use of special materials for the storage containers – for example austenitic steels or coatings with diffusion barrier layers. Otherwise, diffusion losses of the stored hydrogen can occur.

**CHEMICAL PROPERTIES**

The most characteristic chemical property of hydrogen is its flammability (Hollemann/Wiberg 2007). When hydrogen is burned in ambient air, the flame is scarcely visible in daylight, since the flame is characterised by low heat radiation and a high ultraviolet component. In comparison with other fuels, it is striking that hydrogen is combustible in a very broad concentration spectrum. The ignition range of hydrogen, marked by its lower and upper explosive limit, is correspondingly large. The lower limit is at a concentration of 4 vol%, the upper limit at 77 vol%. The liquid and gaseous fuels that are currently in use have much lower ignition ranges. Only ethanol, which is contained in petrol for example, has a higher upper explosive limit, at 27 vol.%.

Its combustion properties make hydrogen an interesting combustion fuel. If hydrogen were to be used in internal combustion engines, the broad ignition limits would allow for extremely lean air/hydrogen gas mixtures. While petrol engines run at a lambda value of 1, and modern diesel engines typically operate at λ ~ 2, lambda values of up to 10 would be possible with hydrogen-prepared combustion engines (Eichler/Köll 2012). Lean combustion is more efficient than stoichiometric combustion and thus minimises fuel consumption.

The autoignition temperature of para hydrogen is 583°C, which is higher than that of conventional fuels. However, the minimum ignition energy of 0.02 MJ is much lower than that of other fuels. Hydrogen is therefore classified as an extremely flammable gas. However, a simple electrostatic discharge (with an energy of around 10 MJ) would also be sufficient to ignite almost any other fuel. The maximum flame velocity of hydrogen is 346 cm/s, which is around eight times higher than that of methane (43 cm/s).

Regarding the thermal behaviour of hydrogen, it has been found that because of the strong bond between the hydrogen atoms of the hydrogen molecule, considerable amounts of energy – in other words high temperatures – are needed to form new molecular bonds. Hydrogen exists almost entirely in atomic form only above a temperature of 6,000 K. In addition to high temperatures, catalysts are also often used for chemical reactions involving hydrogen.

Molecular hydrogen (H₂) is relatively inert. Nevertheless, by punctual heating of a 2:1 hydrogen/oxygen mixture (oxyhydrogen gas) to approximately 600°C, a chain reaction can be started which leads to an explosive propagation of the temperature rise throughout the entire gas mixture. The water vapour formed by the high heat of reaction then achieves a much greater volume than the original hydrogen/oxygen mixture. The sudden propagation of the water vapour leads to a so-called oxyhydrogen or Knallgas reaction.

For that reason, to avoid an oxyhydrogen/Knallgas reaction when working with hydrogen, an oxyhydrogen gas sample should always be taken or oxygen should only be added to the hydrogen at the moment of ignition (Hollemann/Wiberg 2007). Likewise, in gas mixtures containing hydrogen and chlorine gas or fluorine, the reaction to hydrogen chloride or hydrogen fluoride can result in explosive exothermic reactions.

In chemical properties, hydrogen as a combustion and automotive fuel. Nevertheless, handling hydrogen requires care, and in particular compliance with safety regulations.
6 PROCESSES FOR PRODUCING HYDROGEN

DIFFERENT HYDROGEN SUPPLY PATHWAYS

The summary of the energy and greenhouse gas balances is based on the Well-to-Wheel balances of the Joint Research Center of the European Commission, Escur and Concawe (JEC 2014), and the processes behind (JEC 2014); therefore the residence time of the product gas in the reactor (Görner et al. 2015). The higher the operating pressure, the higher the energy consumption (for separation and purification).

The carbon monoxide content is further reduced through further chemical conversion processes such as CO methanation and selective CO oxidation. The purity of the product gas is further increased by subsequent CO2 washing and other physical purification steps (DWW 2015). If other starting materials such as heavy fuel oil are used, the steam reforming process in principle proceeds in the same way. However, the production of the synthesis gas in the first step differs.

Partial oxidation (POX)
Partial oxidation is understood to be the exothermic conversion of mainly heavy hydrocarbons (such as heavy fuel oil or coal) with the aid of oxygen (O2). Thermal partial oxidation takes place under low pressure and at high temperatures from around 1,250°C to around 1,400°C. As heat is released, no external heat source is needed other than the partial combustion of the raw material. The POX reaction equation for hexadecane, a long-chain alkane found in oil, looks like this:

\[ 	ext{C}_{16}	ext{H}_{34} + 8 \text{O}_2 \rightarrow 16 \text{CO} + 17 \text{H}_2 \]

As in steam reforming, a synthesis gas is produced that is converted to hydrogen by means of the water gas shift reaction and gas treatment (Zakkour/Cook 2010). In this process, the longer the chain length of the hydrocarbon used, the lower the hydrogen yield.

A substantial difference from steam reforming is that O2 is used instead of steam as a reaction medium. This O2 is usually produced in an air separation unit, which considerably increases the energy consumption of partial oxidation. However, this is offset to some extent by the extraction of heat from the reaction. In addition, the use of O2 rather than air or more or less eliminates the occurrence of nitrogen in the water gas shift reaction, resulting in a lower energy consumption for separation and purification.

In all, partial oxidation is less efficient than steam reforming; at the same time, however, it offers the advantage of being able to convert a wider range of raw materials, rather than relying on light hydrocarbons (Zakkour/Cook 2010).

Autothermal reforming (ATR)
Autothermal reforming is a combination of steam reforming and partial oxidation. The reforming of methane takes place in accordance with the following reaction equation:

\[ 4 \text{CH}_4 + 3 \text{O}_2 + 2 \text{H}_2\text{O} \rightarrow 4 \text{CO} + 10 \text{H}_2 \]

In the ATR process combining steam reforming and partial oxidation, the high hydrogen yield is determined by the steam reforming step. The necessary process heat is supplied internally by the partial oxidation step.

The advantage of the autothermal reaction, which is not dependent on an external heat supply, is more or less offset by increased investment and operating costs for the air separation unit and a more complicated flue gas purification process.

GASIFICATION
Gasification is a traditional method for producing hydrogen from fossil fuels. It denotes the reaction of a carbon carrier (such as coal) with oxygen or an oxygen-containing gasifying agent to form a synthesis gas. In this process, the raw material that is used is first dried and broken down thermally in the absence of air to form carbon and hydrogen compounds, which are then partially combusted by oxidation (Eichlseder/Klell 2012). In accordance with the following reaction equation, the heated carbon and water vapour produce a synthesis gas consisting of CO and H2:

\[ \text{C} + \text{H}_2\text{O} \rightarrow \text{CO} + \text{H}_2 \]

By the subsequent water gas shift reaction CO again is converted to form CO2 and further water vapour to H2. The various reaction types are distinguished by the design of the gasifier. The gasification process itself can be performed under excess pressure or at atmospheric pressure. The higher the operating pressure, the better the performance of the gasifier.

Gasification generally involves the input of heat (endothermic reaction = allothermal gasification). An autothermal process management, however, uses the heat from the preceding partial oxidation of the fuel. As the feedstock is not yet converted, but used for heat supply, this has a detrimental impact on the efficiency.

Air or a mixture of oxygen and water vapour or carbon dioxide is used as the oxidant or gasifying agent. As in partial oxidation, the product gas that is formed is at its purest when oxygen is used, since the use of air introduces quite a high proportion of nitrogen into the process.

The composition of the resulting synthesis gas, in other words the proportion or purity of hydrogen, is also influenced by the gasification temperature and pressure, by the cooling capacity of the reactor, and by the residence time of the product gas in the reactor (Görner et al. 2013).

2.2 BIOGENIC PRODUCTION

On a global scale, the production of hydrogen from biomass has so far been negligible. In the long term, however, from the perspective of low CO2 hydrogen production, it is conceivable that this manufacturing option could play a part – provided that sufficient requirements for the biomass that is used can be reliably met and that sufficient quantities are available.

In principle there are two methods for producing hydrogen from biomass: thermochemical or biochemical methods. The possibility of generating electricity from biomass and converting it into hydrogen by electrolysis is covered under electrolysis.

THERMOCHEMICAL METHODS
Thermochemical methods are in most cases based on the gasification or pyrolysis of solid or liquid biomass to form a synthesis gas, followed by a further treatment to produce H2 (as with fossil fuels). The “solid biomass” category includes primarily woody and starchy biomass, i.e. forest wood or waste wood and straw, but also starchy energy crops such as miscanthus. Timber is most suitable for gasification, since starchy materials like straw contain too many impurities and, given the tendency to form ash, are not an ideal feedstock for gasification.
processes. Of the various timbers that can be used, untreated wood is most suitable, i.e. forest wood or coppiced wood from short rotation coppices (SRCs).

High-pressure gasification of biomass is complicated by the fact that waste wood tends to be contaminated with stones or nails, which can damage the pressure vessel. For that reason, wood gasification according to IEC (2014) is usually carried out at normal pressure, which has a detrimental impact on the efficiency. The alternative is to use pure forest wood, which reduces the potential for hydrogen production.

Alongside the gasification of solid biomass, however, it is also possible to reform biogenic secondary energy sources or to convert them to hydrogen by partial oxidation. Suitable secondary energy sources include biogas or biomethane (produced by anaerobic fermentation) or bioethanol (produced by alcoholic fermentation). All types of most green biomass are suitable in principle for producing biogas by fermentation (Kaltschmitt et al. 2016). Biogas and biomethane processed to natural gas quality can be used directly in the reformer and converted to hydrogen in the same way as natural gas. In the case of biogas, it need be, a preliminary desulphurisation stage is performed.

The use of vegetable oils, biodiesel or bioglycerol (produced by physicochemical methods) is also possible. Liquid secondary energy sources such as bioethanol, biodiesel, vegetable oils or glycerol sometimes require adjustments to the reformer feed (HyNOW 2012). In particular with respect to the use of secondary energies it should be noted that each additional conversion stage is associated with losses, which adversely affect the overall balance of the product.

**BIOCHEMICAL PRODUCTION**

The biochemical production of hydrogen from biomass using microorganisms is also possible. In this case the biomass can likewise be fermented and processed further, or alternatively water can be split into oxygen and hydrogen by biophotolysis (HyNOW 2012). There are a number of methods available for converting sugar and starch and lignocellulose from biomass into hydrogen. They are based on the use of various microorganisms and (with the exception of one process) draw at least some of the energy they need from sunlight. The most relevant methods are dark fermentation using heterotrophic bacteria, photofermentation using phototrophic bacteria, and biophotolytic splitting of water using green algae or cyanobacteria.

Common to all biochemical methods is the fact that at present they exist only on a laboratory scale and are performed in very small amounts. Market maturity is not yet in sight, since conversion rates and hydrogen yields are still well below a markable threshold and therefore still need to be increased considerably.

With the exception of the biophotolytic process, all biogenic hydrogen production methods require significant volumes of biomass. This could lead to restrictions for large-scale production, since biomass is a renewable raw material whose potential and availability are limited by various requirements, regarding sustainability for example, but also by competing uses (Fritsche et al. 2012; Kaltschmitt et al. 2016).

The charge carrier moves in the electrolyte towards the anode. At the anode (positive pole) the electrons are absorbed by the negative OH– anions. The OH– anions are oxidised to form water and oxygen. Oxygen rises at the anode. A membrane prevents the product gases H2 and O2 from mixing but allows the passage of OH– ions.

$$2\ \text{H}_2\text{O} \rightarrow 2\ \text{H}_2 + \frac{1}{2}\ \text{O}_2 + 2\ e^- \quad (\text{Cathode})$$

$$2\ \text{OH}^- \rightarrow \text{H}_2\text{O} + \frac{1}{2}\ \text{O}_2 + 2\ e^- \quad (\text{Anode})$$

The efficiency of electrolysis is determined by the amount of electricity used to produce an amount of hydrogen. Depending on the method used, the efficiency of water electrolysis is currently in the region of 60 to 80 % (based on the calorific value). Electrolysers consist of individual cells and central system units (balance of plant). By combining electrolytic cells and stacks, hydrogen production can be adapted to individual needs.

Electrolysers are differentiated by the electrolyte materials and the temperature at which they operate: low-temperature electrolysis (LITE), including alkaline electrolysis (Eichleider/Mall 2012). In an alkaline electrolyser (cf. figure 7) the cathode (negative pole) loses electrons to the aqueous solution. The water is dissociated, leading to the formation of hydrogen (H2) and hydroxide ions (OH–).

The high level of interest in hydrogen as a by-product of industry production processes (“industrial residual hydrogen”), especially for use in FCEVs, can be traced back to the time when, in and around the 1980s, work on fuel cell drivelines for vehicles increased and there was intense discussion surrounding “hydrogen as transportation fuel”. The potential of industrial hydrogen for the use of early demonstration fleets of fuel cell vehicles was assessed in a number of studies. Residual hydrogen from industry was intended to serve as an entry point until renewable generated hydrogen was widely available. Furthermore, the industrial distribution infrastructure was regarded as a basis or stepping stone for a universal hydrogen supply system.

At the time, quite significant amounts of hydrogen as a by-product of various industrial operations were being released into the atmosphere rather than being integrated into other production processes (WI/Covestro 2015). Since then, however, energy prices in Germany and Europe have risen, and the industries concerned are now keen either to integrate the accruing hydrogen into their processes or, if that is not possible, to find customers willing to pay a good price for it.

A number of studies have sought to quantify the amount of industrial residual hydrogen available. The EU project “Roads 2 HyCom” (Maisonier et al. 2007) produced among other results a map showing hydrogen production sites in Europe. In this map the hydrogen sources were broken down into three categories: the “merchant” category supplies hydrogen to other industrial customers, while the “captive”
In the course of the energy transition, the proportion of renewable energies in electricity generation has risen markedly. Wind power and photovoltaics have seen the greatest expansion. However, the availability of these intermittent and non-dispatchable renewable energies (variable renewable energies, VRE) fluctuates over time. At the same time, because of its physical properties, supplying electricity requires a constant balancing of supply and demand. If the proportion of renewable energies exceeds roughly one-quarter of electricity generation, special/additional measures are necessary in order to integrate fluctuating renewable energy supplies. Otherwise it may be necessary to limit the production or use of renewable energies.

Alongside other demand and supply measures, energy storage can play an important part in improved system integration. Until now, pumped-storage hydro power plants have dominated electricity storage capacity – although they account for less than 3% of global electricity generation. Short-term electricity storage in batteries for small plants is developing dynamically. However, long-term storage of larger surplus amounts of electricity requires new types of storage, such as chemical storage in the form of hydrogen (IEA 2016a).

Hydrogen can be obtained by electrolysis from renewable energies (“green hydrogen”) in fuel refining (hydrogenation) or for fuel production by means of synthesis into liquid fuels (Power-to-Liquids) and using the generated hydrogen as a basic chemical (Power-to-Chemicals, Power-to-Plastics).

Power-to-X is currently still in the research and development stage. Various projects explore fundamental questions of feasibility and economic viability (BVMV 2014; Graf et al. 2014; Sundmacher 2014; Zuberbuhler et al. 2014). One disadvantage of PtX concepts is, undoubtedly, the large number of conversion steps. This leads to low efficacies along the entire supply and use pathways (IEA 2015b). On the other hand, hydrogen as an energy storage medium and/or its potential for conversion in further energy carriers allows for an accelerated expansion and use of surplus renewable energies. Not least for that reason, an important role has been given to hydrogen as an energy store and to PtX supply and use pathways towards a greenhouse gas neutral energy industry (UBA 2014).

### 9 POWER-TO-X PATHWAYS

**POWER-TO-GAS**

- CO2
- Methanation
- Synthesis
- Methane riches
- Power generation
- Electrolysis
- Power
- Fuel
- Storage capacity
- Gas grid
- Power-to-liquids
- CO2
- Synthesis
- Fuel
- Power
- Fuel
- Storage capacity
- Gas grid
- Power generation
- Electrolysis
- Power
- Fuel
- Storage capacity
- Gas grid
- Power-to-liquids
- CO2
- Synthesis
- Fuel
- Power
- Fuel
- Storage capacity
- Gas grid
- Power generation
- Electrolysis
- Power
- Fuel
- Storage capacity
- Gas grid
- Power-to-liquids
- CO2
- Synthesis
- Fuel
- Power
- Fuel
- Storage capacity
- Gas grid

**POWER-TO-LIQUIDS**

- CO2
- Synthesis
- Jet fuel
- Diesel
- Petrol, biofuel
- Jet fuel
- Diesel
- Petrol, biofuel

### 2.5 COMPARISON OF SUPPLY PATHWAYS

The previous sections of this chapter introduced various hydrogen production technologies. These technologies can be differentiated not only in terms of the energy sources used (fossil or renewable, for example) but also in terms of the size and location of the production unit depending on demand and on the supply strategy, hydrogen is generated decentralised in small plants directly at the point of use or in large centralised plants and subsequently transported by pipeline or lorry to the dispensing stations.

In practice there will also be combinations of centralised and decentralised production, in regional supply for example, but for simplification reasons they are not described here. Thermal conversion from the fossil fuels coal, oil and above all natural gas still dominates. As a result of which the availability of individual “by-products” is falling sharply overall.

The project “CO2, ReUse and NRW” (KME/ Covostra 2015) provided a detailed insight into the production, distribution and use of industrial hydrogen. The bulk of industrial hydrogen is produced specifically for its intended purpose (mostly chemical industry). Within this context, refineries too have become net consumers of hydrogen. Only a relatively small proportion of 9% of the total amount of hydrogen produced can be considered to be available for external applications. Therefore, little or no industrial hydrogen is available for other applications, such as transportation fuel.

By contrast, according to a survey by (Cox 2011), in the USA there is still potential in residual hydrogen. The most important source for this is the chlor-alkali electrolysis; however, landfill gas and biogenic gases are also regarded as a potential source of by-product hydrogen. In this context considerable importance is attached to the availability of gas processing plants.

### SUPPLY PATHWAYS

The results are shown in figures 10 and 11. All pathways are shown as being “centralised” in large production units, where “centralised” still means domestic production. The possibility of producing hydrogen on a large scale using solar power in North Africa or offshore wind power in Northern Europe, for example, and shipping it to Germany has been excluded from this analysis. For various reasons, not only technical but also geopolitical, the impact of implementing this option, which is more of a long-term objective, cannot yet be assessed. The sensitivity analysis illustrates the effects of decentralisation, characterised firstly by the less efficient production and secondly by the elimination of or at least the considerable shortening of the transport route.

In considering the energy efficiency of the different hydrogen production and supply pathways, differences between the primary energy sources are evident (figure 10). The EU electricity mix/electrolysis pathway stands out because the cumulated energy input is 4 to 5 times higher than that of the other pathways. By contrast, the differences between natural gas reforming and electrolysis from variable renewable energies (in this case wind) in terms of the height of the bars are slight.

Nevertheless, the type of energy source used must be taken into account: electrolysis from renewable energies uses more than 70% renewable energies and consumes only small amounts of fossil and nuclear resources (for transport and for production and dismantling of the wind energy converters used). By contrast, the proportion of renewable resources in the gas reforming pathways is less than 5%. One exception to this rule is the “biogas mix” pathway, half of which is supplied by waste-based biogas and which thus contains a higher proportion of renewable energy.
In terms of greenhouse gas emissions the reforming pathways represent an average value which does not vary substantially according to the origin of the natural gas or the type of import (as Compressed Natural Gas, CNG, by pipeline or in liquefied form as LNG, Liquid Natural Gas). The greenhouse gas intensity can be reduced significantly by adding processed biogas, so-called biomethane, which has similar properties to natural gas. However, this is very much dependent on the origin and the type of the raw materials from which it is produced. The use of biomethane derived from municipal waste has significantly lower greenhouse gas emissions than biomethane based on energy crops or slurry (DBFZ 2014). The addition of biomethane to natural gas and its use in hydrogen production generally occurs as a balance sheet calculation rather than by physically transporting the biomethane to the reforming plant.

Even more relevant than the type of gas used for reforming is the greenhouse gas intensity of the electricity used for electrolysis. In terms of the carbon footprint, the EU electricity mix and the electrolysis from renewable energies pathways differ by a factor of 17.

If solely renewable electricity is used, the hydrogen that is produced is almost emission-free, with around 13 g CO₂/MJ H₂. On the other hand, if the average European electricity mix is used for electrolysis, the greenhouse gas emissions produced are some 2.2 times higher than in natural gas reforming.

Therefore, if hydrogen is to be made available sustainably and on a large scale, hydrogen production needs to be restructured to combine the production with the required electricity. For this purpose, the required electricity must be produced specifically for that purpose. The scale of the transition of electricity generation that is needed shows a comparison: if hydrogen is to be produced by electrolysis from a partly decarbonised electricity grid with the same greenhouse gas intensity as for the natural gas reforming pathway, specific greenhouse gas emissions from the electricity that is used must be about 56 g CO₂/MJ electricity. Compared with the current levels of approximately 150 g CO₂/MJ electricity, the grid’s greenhouse gas intensity would therefore have to be reduced by approximately two-thirds.

The values for the selected hydrogen production pathways are taken from the JEC study (JEC 2014) and reflect the situation across Europe. It is assumed that these values also apply to Germany. There are differences between the EU and Germany, especially in regard to the electricity mix.

As a consequence of the high proportion of coal used in its production, the German electricity mix has a higher CO₂ intensity. However, the conclusions that can be drawn are not fundamentally different.

There are also similar programmes and resulting studies in other regions of the world, for example in California and other states of the USA. The WalltoWheel emissions for typical hydrogen production pathways were analysed by the Argonne National Laboratory in the “Greenhouse gases, Regulated Emissions, and Energy use in Transportation” model (GREET 2015). The values are in the same order of magnitude as those from the JEC study and therefore support the conclusions set out here.

2.6 PRODUCTION COSTS - CURRENT AND PROJECTED

Essential parameters of the various production pathways also include, in addition to the energy uses and greenhouse gas emissions described above, the production costs. These are not included in (JEC 2014) but have been added from other literature references. The structure and components of the pathways in the literature differ in some details, such as plant size and capacity utilisation, raw material costs, etc., from the pathways considered above.

Here only the pure production costs are considered, infrastructure and distribution costs (for road transport) are covered elsewhere. Key controlled variables for the analysis and compilation of production costs are the costs or prices of the primary energy sources (natural gas, biomass, electricity, etc.) and energy costs for conversion; the type, size, capacity, and utilisation of the conversion plant and the conversion efficiency or yield of hydrogen.

The production costs for the centralised biomass-based pathways, at an average of around 3.3 €/kg H₂, up to a maximum of 7.4 €/kg H₂, lie somewhere between those for natural gas reforming and electrolysis. Here too the dependency on biomass production costs should be noted; depending on what sustainability requirements are implemented, these costs could rise sharply in future if sustainable biomass becomes scarcer. In the short to medium term outlook (2020 and 2030), the data situation becomes much sparser. For decentralised natural gas reforming, only one set of cost data is available, with no spread. For the biomass pathways the...
IN SUMMARY

Hydrogen can be produced from a large number of primary energy sources and by various technical processes. The most important primary energy source for hydrogen production today is natural gas, with a share of 70%, followed by oil, coal and electricity (as a secondary energy). Steam reforming from natural gas is the most important method of hydrogen production. Electrolysis from electricity currently accounts for around 5% of global hydrogen production. In addition, only a small amount of unused residual hydrogen, generated as a by-product of industrial production processes, is (still) available.

The importance of renewable energies in hydrogen production is still low, although it will increase in future. Electrolysis from renewable electricity is seen as offering huge potential for the future. Hydrogen can also be produced from biomass, provided that there is sufficient sustainable biomass potential.

3 ENERGY DENSITY OF FUELS

The energy density (LHV) of hydrogen is thus of hydrogen and other gaseous and liquid energy carriers and fuels.

3.1 STORAGE

The way in which an energy carrier is stored is greatly influenced by its energy content. The energy content of an energy source is determined by its calorific value or more precisely by its lower and higher heating value. The lower heating value (LHV) is defined as the amount of usable heat that is released in a (theoretically) complete combustion. The higher heating value (HHV) additionally takes into account the heat of condensation contained in the water vapour, although this cannot be used by motor vehicles. The calorific or heating value is a specific quantity and is usually based on the mass of the energy source, so it is stated in MJ/kg or kWh/kg, for example. Using the density (kg/m³), the mass-based calorific value can also be converted into a volumetric energy density, which is then stated in MJ/m³ or kWh/m³. Figure 13 shows the gravimetric and volumetric energy densities of hydrogen and other gaseous and liquid energy carriers and fuels.

INTEGRATION

Coupling in integrated energy schemes.

Hydrogen produced on an industrial scale from (surplus) renewable energies, and unlike electricity it can be stored and transported as a gas, liquid or solid.

The importance of hydrogen in the energy transition is already being felt as it can be used alone or in combination with other energy carriers.

Hydrogen can be used as a carrier of energy (also chemical energy). Hydrogen produced from renewable energies produces the lowest greenhouse gas emissions. The primary energy input for electrolysis based on conventional electricity is high, whereas that for natural gas and biomass reforming and for renewable electrolysis is low. However, electrolysis from renewable electricity uses a high proportion of renewable primary energy and only small amounts of fossil primary energy.

Of all the production methods and supply pathways considered, centralised hydrogen production is more cost-effective than decentralised production. Centralised natural gas reforming is the most cost-effective method. For newer production pathways, in particular electrolysis from renewables, substantial cost reductions still need to be achieved.

It can be seen that hydrogen as an energy carrier has by far the highest gravimetric energy density (lower heating value), at 120.1 MJ/kg, the higher heating value (not shown in figure 13) is even as high as 141.88 MJ/kg. The mass-based energy density (LHV) of hydrogen is thus almost three times higher than that of liquid hydrocarbons.

However, the volumetric energy density of hydrogen is comparatively low. Under ambient conditions the vapour pressure is almost on the zero line, at just 0.01 MPa. Therefore, for practical handling purposes, the density of hydrogen must be increased significantly for storage purposes. The most important hydrogen storage methods, which have been tried and tested over lengthy periods of time, include physical storage methods based on either compression or cooling and a combination of the two (hybrid storage). In addition, a large number of other new hydrogen storage technologies are being pursued or investigated. These technologies can be grouped together under the name materials-based storage technologies. These can include solids, liquids or surfaces. Figure 14 shows an overview of the available hydrogen storage methods. As yet only physical storage by compression and liquefaction have any commercial relevance.

PHYSICAL HYDROGEN STORAGE

Physical storage methods are the most mature and the most frequently used. A distinction is made between high-pressure storage and cooled hydrogen storage. As hydrogen has to be cooled down to very low temperatures in order to liquefy, the term cryogenic hydrogen storage is also used. Finally, if compression and cooling are combined, this is also referred to as hybrid storage.

High-pressure storage

Compressed Gaseous Hydrogen, CGH₂. From production through intermediate storage and on to distribution to the end user, hydrogen is handled at different gas pressures. A low-pressure storage tank operates at just 50 bar. For intermediate storage in high-pressure tanks or gas cylinders, pressures of up to 1,000 bar are technically possible. Only solid steel or steel composite pressure vessels...
CGH2 – have become the norm for use in
specific energy density is 4.8 MJ/l. 

volumetric energy density increases to 2.9
bar – technically referred to as CH2 or
Compressed (gaseous) hydrogen with
compression leads to a volume reduction.

End users
distributed at a regional level.
Consists of depleted gas reservoirs. In
and common form of underground storage
only a relatively small proportion of these
surplus renewable energies. However,
America could potentially be used as large
natural gas stores in Europe and North
in a few locations in the USA and Europe
IEA 2015b).
In particular, the underground natural gas stores in Europe and North America could potentially be used as large
reservoirs for hydrogen generated from
surplus renewable energies. However,
only a relatively small proportion of these
are storage caverns; the most prominent
and common form of underground storage
consists of depleted gas reservoirs.

In addition, the natural gas stores are unevenly
distributed at a regional level.

End users, by contrast, require a more
compact form of storage. According to the
Boyle-Marriott gas law, the volume of an
ideal gas at a given temperature behaves
in an inversely proportional manner to
its pressure. Although real gases are not
indefinitely compressible, in this case too
compression leads to a volume reduction.

Compressed (gaseous) hydrogen with
storage pressures of 350 bar or 700
bar – technically referred to as CH2, or
CGH2, have become the norm for use in
the mobility sector. Since hydrogen heats up when it is compressed, in some cases it is
handled at excess pressures or the
hydrogen gas is precooled. If hydrogen is
compressed to 350 bar [CGH2], the
volumetric energy density increases to 2.9
MJ/l, when compressed to 700 bar the
specific energy density is 4.8 MJ/l.

Liquefied Hydrogen, LH2
As well as storing gaseous hydrogen under
pressure, it is also possible to store cryo-
genic hydrogen in the liquid state. Liquefied
hydrogen (LH2) has a specific energy
density of 8.5 MJ/l, which is higher than
that of compressed natural gas (CNG)
(approximately 7.2 MJ/l). As such, LH2 is
some way behind the liquefied gases (LPG
25.3 MJ/l) and LNG (21 MJ/l).

LH2 in demand today in applications requiring high levels of
purity, such as in the chip industry for exam-
ple. As an energy carrier, LH2 has a higher
energy density than gaseous hydrogen, but
it requires liquefaction at -253 ºC, which
involves a complex technical plant and an
extra economic cost.

When storing liquid hydrogen, the tanks
and storage facilities have to be insulated
in order to keep in check the evaporation that
occurs if heat is carried over into the
stored content, due to conduction, radiation
or convection. Existing storage facilities
are rarely able to prevent such effects
completely, i.e., they can only delay them
IEA 2013].

LH2 tanks or storage vessels generally
have a double hull design, with a vacuum
between the inner and outer container.
To regulate a pressure rise caused
by evaporating hydrogen in the inner
container, small amounts of gas have to
be released (boil-off). Modern systems are
optimized so that boil-off no longer leads to
substantial losses.

Tanks for LH2 are used today primarily in space
travel. Accordingly, the largest tank is
located at the Cape Canaveral rocket
launch site; it holds around 3,800 m3 of
liquid hydrogen (JBST 2010).

Cold- and cryo-compressed
Hydrogen [CcH2]
In addition to separate compression or
cooling, the two storage methods can be
combined. When a gas is cooled, it follows
from Gay-Lussac’s law that the volume of an
ideal gas held at constant pressure
behaves proportionally to the temperature;

in other words, if the temperature falls by
one Kelvin, the volume of an (ideal) gas
drops by 1/273.15. This relationship also
applies in principle to real gases. That is
why hydrogen is cooled first.

Depending on how much the hydrogen is
cooled, it is referred to as cold-compressed
hydrogen (above 150 K) or cryo-com-
pressed hydrogen (CcH2). Cryo-com-
pressed hydrogen is cooled to tempera-
tures close to the critical temperature, but it
still remains gaseous. The cooled hydrogen
is then compressed (US DOE 2006, BMW 2012]. CcH2 is a further development of
hydrogen storage for mobility purposes.

The first field installations are already
in operation. It is not yet clear whether
CcH2 will develop into the new storage
standard for road transport. The advantage
of cold or cryogenic compression is a
higher energy density in comparison to
compressed hydrogen. However, cooling
requires an additional energy input.

Slush Hydrogen (SH2)
An additional option for compressing
liquefied hydrogen (LH2) is to cool it down
further, to its melting point. That is because
at the melting point, before it becomes
completely solid, hydrogen first changes
into a kind of slush or gel. Slush or gelled
hydrogen (SH2), which is composed of
roughly equal proportions of solid and
liquid hydrogen, has – corresponding
to its solid hydrogen components – a
16% higher storage density than liquid
hydrogen. Slush hydrogen has primarily
been investigated as a fuel for space travel
(Eichlseder/Klüss 2012).

In addition to the volume and weight of the fuel, the weight of
the tank system is relevant, since heavy tank systems increase
rolling, grade and acceleration resistance and hence the fuel
and energy consumption of a vehicle. Vehicle tanks for liquid
fuels have a very favourable ratio of transported energy con-
tent to overall mass of tank system plus content.

Figure 16 shows a 55-litre tank for a modern compact/mini-
sized car with a net weight of just 15 kilograms. The storage
density of petrol relative to the overall tank system including
its energy content is therefore over 30 MJ/kg. With smaller
storage capacities and vehicle tanks for more efficient dri-
ve systems (such as petrol hybrid vehicles), the ratio would
be (somewhat) less favourable (JEC 2013).

By contrast, the ratio of hydrogen energy content to hydro-
gen tank plus tank content is around 6 MJ/kg. In the medium to
long term, the goal is to achieve a gravimetric system density
of 9 MJ/kg (US Drive 2015). Similar to batteries in a hybrid
gasoline vehicle, fuel cell vehicles also need a (smaller)
tration battery. Depending on the drivetrain configuration,
the battery adds additional weight. Nevertheless, fuel cell
vehicles achieve ranges comparable to those of internal
combustion engine cars because of their higher drive
efficiency.

Finally, the gravimetric storage density of hydrogen tank
systems is significantly higher than that of battery electric
vehicles. Current battery technology achieves storage
densities of 0.3 MJ/kg and 1.116 MJ/kg is considered
achievable in the medium to long term (VDE 2015). As a
consequence, battery electric vehicles have much shorter
ranges and the vehicle weight is greater.
Hydrogen storage systems

In metal hydride storage systems the hydrogen forms interstitial compounds with metals. Here molecular hydrogen is first adsorbed on the metal surface and then incorporated in elemental form (H) into the metallic lattice with heat output and released again with heat input. Metal hydrides are based on elemental metals such as palladium, magnesium and lanthanum, intermetallic compounds, light metals such as aluminium, or certain alloys. Palladium, for example, can absorb a hydrogen gas volume up to 900 times its own volume (Martine/Mühle 2010).

The storage density of metal hydride storage systems is far in the region of 1.5 wt% at room temperature, which means that 1.5 kg of hydrogen could be stored in a storage mass of 100 kg. In recent years, complex hydrides have enabled the storage capacity to be increased to up to 5.5 wt% (e.g. 5.5 kg H₂ in a 100 kg storage mass) (EA NRW 2013).

Substantial drawbacks to hydride storage are firstly the large amount of heat energy used for charging, and secondly – especially for applications in transport – the high mass and the slow absorption and release of hydrogen. Advantages include the filter effect of metallic storage, allowing high-purity hydrogen to be discharged, and the low potential of accidental release.

Liquid organic hydrogen carriers (LOHCs)

Liquid organic hydrogen carriers (LOHCs) represent another option for binding hydrogen chemically. LOHCs are chemical compounds with high hydrogen absorption capacities. They currently include, in particular, the carbazole derivative N,N-dicyclohexylamine, but also toluenes, which is converted to metacyclohexylamine by hydrogenators, dibenzylamine, ammonia borane and formic acid (Van Wild et al. 2010).

Dehydrogenated LOHCs (unsaturated hydrocarbons) absorb hydrogen in the presence of a catalyst and at pressures of 30 to 50 bar and temperatures of approx. 150°C to 200°C. The heat released by this process (exotherm) can be used elsewhere – for heating purposes or for preheating ahead of dehydrogenation, for example. The hydrogenated carbazole derivative has comparable physicochemical properties to diesel fuel and can be stored and transported accordingly (Teichmann et al. 2011). Discharge takes place by dehydrogenation, which requires a heat input of approximately 250 to 300°C (endothermic reaction). The released hydrogen may in some cases also need to be freed from LOHC vapour.

Surface storage systems (sorbents)

Finally, hydrogen can be stored as a sorbate by attachment (adsorption) on materials with high specific surface areas. Such sorption materials include, among others, microporous organometallic framework compounds (MOFs), microporous crystalline aluminosilicates (zeolites) or microscopically small carbon nanotubes. Adsorption materials in powder form can achieve high volumetric storage densities. The sorption temperatures are generally well below the discharge temperatures for liquid and solid storage materials. Adsorption storage materials as hydrogen stores are still the furthest removed from practical implementation in the field.

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Infrastructure elements that were installed at the time, such as pipelines, gas installations, seals, gas appliances etc., were designed for the hydrogen-rich gas and were later modified with the switch to natural gas. It can be assumed that many of the gas transport networks, distribution lines and storage facilities that were operated in the past are still in use today (Müller-Syring et al. 2013). In Leeds (UK), for instance, the possibility has been explored of converting the existing natural gas network in the region (used primarily for municipal heating supply) entirely to hydrogen (Sodar et al. 2016).

Many countries have looked at adding hydrogen into the existing natural gas networks. For the USA, according to (NREL 2013b), it would be possible to introduce amounts from 5 vol% to 1.5 vol% hydrogen without substantial negative impact on users or the pipeline infrastructure. At the same time, the larger additions of hydrogen would in some cases require expensive conversions of appliances.

In Germany this limit has been set somewhat lower, at up to 10 vol% (Müller-Syring et al. 2013; Müller-Syring/Hasel 2014). In principle, gas at concentrations of up to 10 vol% hydrogen can be transported in the existing natural gas network without the risk of damage to gas installations, distribution infrastructure, etc. However, a number of components have been listed that are still considered to be critical and to be generally unsuitable for operation with these hydrogen concentrations. For CNG vehicles, the currently authorised limit value for the proportion of hydrogen used is only 2 vol%, depending on the materials built in (UNECE 2013). Given their length, the large gas networks in many industrial countries could store considerable amounts of hydrogen. A number of different technical methods are available for recovering hydrogen transported by natural gas pipeline from a natural gas/hydrogen mixed gas (NREL 2013b): pressure swing adsorption (PSA), the membrane process, or electrochemical gas separation. However, all separation processes require additional technical effort and energy input.

TRANSPORT ECONOMY

The various transport possibilities each require specific infrastructure and also involve different fixed and operating costs as well as varying levels of energy input and transport capacity. Depending on the transport task (i.e. the amount of hydrogen to be transported, the distance, the priority of low costs, etc.), the most suitable option must therefore be chosen in each case.

If hydrogen is required in small amounts on a laboratory scale, it is typically transported by lorry in gaseous form in pressure cylinders. This option is relatively expensive for larger amounts, since the greater the volume of hydrogen to be transported, the larger the number of pressure cylinders required. However, in comparison to liquefaction or to a pipeline network, there are virtually no fixed costs, so this is the best option for small amounts and short distances (Yang/Ogdin 2007). It is also a flexible option, since it is available for any route and at any time and the necessary amounts can also be increased (albeit with additional operating costs) and reduced if it is available. Liquid hydrogen trucking is the preferred option for larger volumes over larger distances. The additional cost for hydrogen liquefaction is then offset by the lower trucking cost.

For the transport of very large hydrogen volumes a comprehensive pipeline network is ideal. This option is dominated by the costs of building the pipeline infrastructure. Once it has been built, the increase in specific transport costs for larger volumes is negligible. A pipeline is thus the most cost-effective choice for large transport volumes, whereas for small amounts the fixed costs are very difficult to recover (Yang/ Ogdin 2007). This conclusion applies to all gaseous and liquid substances to be transported, irrespective of the specific properties of hydrogen.

PRODUCT QUALITY

Hydrogen is used in both gaseous and liquid form. Liquid hydrogen is purer than gaseous hydrogen, since the cryogenic temperatures cause a number of accompanying substances to freeze and drop out. The hydrogen quality is differentiated by degree of purity. Hydrogen is available up to a purity grade of 7.0; this corresponds to a purity of 99.99999%. What should be the quality requirements for hydrogen as an energy carrier?

Impurities and accompanying substances in hydrogen are dependent on the manufacturing process. Thermochemical production methods may give rise to more accompanying substances which, depending on the subsequent application, require the hydrogen to undergo a multistage post-production purification treatment. Hydrogen from electrolysis contains exceptionally few undesired accompanying substances – principally water vapour (H₂O).

Hydrogen as a feedstock has long been used for industrial processes, either as a feed material for chemical production through to semiconductor production, or for energy purposes as a supplementary energy source in thermal processes. Its use in fuel cells is relatively new.

SAFETY

Hydrogen is a combustible gas. And if combustible gases are released, they can form explosive mixtures with air. Hydrogen is known from chemistry lessons in particular for the so-called exothermic hydrogen or Knallgas explosion. It is therefore legitimate to ask (DVW 2011): How safe is hydrogen? What factors have to be taken into account to ensure hydrogen is handled safely?

Safety-related information about substances and mixtures is summarised in safety data sheets. ISO Technical Report 15916 (2015) contains international guidelines for the safe handling and storage of gases and liquid hydrogen. Safety requirements for specific applications are laid down in other ISO standards referenced in that report; they include, for example, ISO 19880 (2016), which describes safety and performance requirements for compressed hydrogen refuelling stations for passenger cars and other motor vehicles.

First of all, hydrogen by itself is not explosive; it is not self-igniting, decodable or oxidising. Moreover, hydrogen is not toxic, corrosive, radioactive, foul-smelling, water-polluting or even carcinogenic. Hydrogen can however displace atmospheric oxygen and as such have an asphyxiating effect. Its most obvious safety-related feature is its high flammability and the broad ignition limits in hydrogen-air mixtures from 4 to 77%.

Yet hydrogen cannot burn on its own. It requires an oxidant (air/oxygen) to do so, along with an ignition source, such as an electric spark. If hydrogen in pure form is brought together with air/oxygen and an ignition source, it burns almost invisibly. For the safe handling of hydrogen, it follows that:

Unlike liquid fuels hydrogen is stored and transported in pure form and in closed resp. completely sealed systems/tanks. Hydrogen pressure tanks, which are most commonly used,
4.1 MATERIAL AND INDUSTRIAL APPLICATIONS

Hydrogen is a highly versatile basic chemical, which is used in chemical production and industry to produce, process or refine intermediates and/or end products. It is estimated by (Zakkour/Cook 2010) that between 4.5 Mt/a and 50 Mt/a of hydrogen are produced worldwide, and around 7.8 Mt/a are used in Europe (Le Duigou et al. 2011).

AMMONIA (FERTILISERS)

The most important hydrogen-nitrogen compound is ammonia (NH₃), also known as azane. Technically, ammonia is obtained on a large scale by the Haber-Bosch process. This process combines hydrogen and nitrogen together directly by synthesis. To this end, the starting materials nitrogen and hydrogen must first be obtained. In the case of nitrogen this is achieved by low-temperature separation of air, while hydrogen originates today from natural gas steam reforming.

Ammonia is synthesised at temperatures of 500°C and pressures of 200 bar. As triple-bonded atmospheric nitrogen (N₂) is very unreactive, the presence of an iron-based catalyst is required. The elements hydrogen and nitrogen react together in the proportion 3:1 in accordance with the following reaction equation:

\[ 3 \, \text{H}_2 + \, \text{N}_2 \rightarrow 2 \, \text{H}_2\text{N} \]

The yield of the Haber process, i.e. the conversion rate of nitrogen (N₂) to ammonia ([NH₃]) is modest, at below 20%, so substantial recycling of unreacted gases occurs.

Ammonia itself is a colourless gas with a pungent odour. It is readily water-soluble. Almost 90% of ammonia goes into fertiliser production. For this purpose, a large part of the ammonia is converted into solid fertiliser salts or, after catalytic oxidation, into nitric acid (HNO₃) and its salts (nitrate) (Hollemann/Wiberg 2007; Martinek/Muller 2010).

Owing to its high energy of evaporation, ammonia is also used in refrigeration plants as an environmentally friendly and inexpensively produced refrigerant; its technical name is “green hydrogen”.

It is expected that there will be a further rise in hydrogen demand in refineries worldwide. One reason for this trend is the need to achieve higher processing depths for each barrel of crude oil. Another is the worldwide increasing quality requirements for fuels (e.g. freedom from sulphur and metals), especially in the emerging markets (IEA 2011a). Better fuels are needed to comply with more stringent engine standards and stricter exhaust gas regulations.

Finally, not only mineral oils, but also vegetable oils can be hydrogenated. The latter can either be hydrogenated in refineries together with fossil intermediates (cohydrogenation) or in separate biofuel plants. Hydrogenated Vegetable Oil (HVO) is a fungible paraffinic fuel comparable to Diesel fuel. The hydrogenation process is also used in food chemistry to harden oils and fats and in the plastics industry for polymer production.
METHANOL
Hydrogen is also an important basic substance for producing methanol (CH₃OH). The production of methanol (methanol synthesis) takes place by means of the catalytic hydrogenation of carbon monoxide (Hollmann/Wiberg 2007). Here a mixture of carbon monoxide and hydrogen – also known as water gas or synthesis gas – is passed over suitable catalysts. Under pressure and at elevated temperature, methanol is formed almost exclusively, in accordance with the following reaction equation:

CO + 2 H₂ → CH₃OH

Methanol or methyl alcohol is a simple alcohol with a high boiling point of 64.7°C and a high heat of combustion and is used in catalytic combustion (Weber 1988). In the presence of certain metals, it can be used as a fuel in diesel engines (hot) combustion processes. The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014). The formation of nitrogen oxides (NOx) in the presence of oxygen and (hot) combustion are well below the hydrogen limits (Čermák 2014).

ONE APPLICATION
Hydrogen can be used directly as a fuel in internal combustion engines. It is also used in direct methanol fuel cells, for reforming, in PEM fuel cells. Fuel additives are produced from methanol, and it is used to transmesterry vegetable oils to form methyl esters (biodiesel). Methanol is also a central chemical raw material, from which important chemical intermediates like formaldehyde (CH₂O), acetic acid (CH₃CO₂H), and others are synthesised. The demand for methanol has been rising steadily since 2009. A further growth in the demand for methanol has been expected (Johnson 2012).

OTHER APPLICATIONS
The other applications, which in total make up around 10% of hydrogen usage, consist of two groups:

Firstly, hydrogen is used to produce a large number of other important chemical compounds. These include (according to IBST 2010) base materials for paints and synthetic fibres, various raw materials and precursors for nylon production and polytene elastomer production, and use for the plasticisation and elastisation of plastics.

Secondly, hydrogen is needed in other industrial applications; these include metalworking (primarily in metal alloying), flat glass production (hydrogen used as an inerting or protective gas), the electronics industry (used as a protective and carrier gas), in deposition processes, for cleaning, in etching, in reduction processes, etc., and applications in electricity generation, for example for generator cooling or for corrosion prevention in power plant pipelines (IBST 2010).

The direct reduction of iron ore – i.e. the separation of oxygen from the iron ore using hydrogen and synthesis gas – could develop into an important industrial process in steel manufacturing, because in the traditional blast furnace method, large amounts of carbon are released (IBST 2010). While direct reduction with natural gas is now well-established in steel production (World Steel Association 2015), corresponding production methods based on hydrogen so far exist only on a pilot scale.

4.2 ENERGY APPLICATIONS
In terms of energy applications, hydrogen is above all a secondary energy source and chemical energy store. The energy it contains can be used either in thermally operating heat engines or in galvanic (fuel) cells.

When hydrogen (H₂) is burned with pure oxygen (O₂), water is formed in accordance with the following reaction equation:

2 H₂ + O₂ → 2 H₂O

In contrast to the combustion of hydrocarbons, no carbon dioxide is formed in this process. If hydrogen is burned with air, nitrogen oxides are also produced. Very high temperatures are reached in hydrogen combustion – above 2,000°C, up to 3,000°C, depending on the oxygen content of combustion air.

Although hydrogen is generally a clean and potent fuel with high energy content and attractive combustion properties, hydrogen’s use for energy purposes now rarely takes off (but combustion). There has been little further research and development in hydrogen fuelled internal combustion engines in the recent past. Only in space travel hydrogen is still used as a propellant for rocket engines. Other than that, only hydrogen accruing as a by-product in industry is still occasionally co-combusted, if no economic use can be found for it.

Given the technical progress made in fuel cell technology in recent years, but also because of the technical requirements applying to hydrogen-powered heat engines, the use of hydrogen as a fuel is now focused almost entirely on the fuel cell.

FUEL CELL
The fuel cell principle was discovered as early as 1839/39. At the time, however, the fuel cell was unable to make any inroads against the steam engine/genera tor combination. Unlike heat engines, a fuel cell can convert chemically bound energy into electrical energy directly, i.e. without detouring via a thermal power process.

The optimum efficiency of heat engines is denoted by the Carnot efficiency (Bosch 2014). This is dependent on the ratio of the upper combustion temperature to the lower incoming air temperature. In fact, heat engines cannot convert the entire heat of the combustion process into mechanical energy, only a part of it.

The generation of electricity via heat engines also requires the use of a generator. Moreover, real heat engines operated by petrol or diesel processes remain well below theoretical Carnot efficiencies. And when operated with fossil fuels they emit both air pollutants and greenhouse gases.

In fuel cells, the energy contained in hydro gen is converted into electrical and heat energy. In this process, 282 kilojoules of energy are released per mol of hydrogen. The conversion of this released energy (reaction enthalpy) into electrical energy determines the maximum efficiency of a fuel cell. In theory, fuel cells can reach cell efficiencies of over 80%. However, owing to voltage losses the efficiencies that are actually achievable are lower (Eichtbauer/Kleff 2012).

Since a fuel cell produces waste heat as well as electricity, it can also be used in combined heat and power processes. If the waste heat is at a sufficiently high temperature level, a combined heat and power power process can be added downstream. That is the case with the high-temperature fuel cells (SOF and MCFC), this gives rise to much higher overall efficiencies than in pure thermal engines.

The direct conversion of chemical energy is already known from batteries. These have a finite internal store of energy. A fuel cell can provide a continuous supply of electricity for as long as the cell is fed with fuel. In the simplest case the fuel is hydrogen, which combines with oxygen in a reaction to form water. By spatial separation into two half-cells – by means of an electrolyte, membrane and/or diaphragm – the two substances are unable to react with each other, so a controlled reaction can occur.

Depending on the fuel cell type, the temperatures reached during catalytic combustion are well below the hydrogen combustion temperatures, at approx. 600°C to 1,000°C. The process is also referred to as cold combustion. The formation of nitrogen oxides (NOx) in the presence of oxygen is avoided in catalytic combustion (Weber 1988).

STRUCTURE & FUNCTIONING
While electrolysis breaks down water into its constituents oxygen and hydrogen using direct current, the reverse process of electrolys is, i.e. the recom bination of oxygen and hydrogen to form water with production of direct current takes place in a fuel cell. The basic structure and operation of a fuel cell is illustrated in figure 20.

In addition to the schematic representation shown here, the following elements are also needed to operate a fuel cell: conditioning of fuel, air and waste gas, cooling circuit, power circuit, humidifier line, measurement and control technology, safety equipment and additional equipment for startup.

A fuel cell system consists of individual fuel cells connected in series – also known as stacks. The core component of the fuel cell is the membrane electrode assembly (MEA), which determines the performance of the fuel cell. It consists of two porous, catalyta-doped electrodes (cathode and anode), an electrolyte (ionic conductor) arranged between them, and the gas diffusion layers.

The electrolyte separates the gases from each other, but is permeable for certain ions (electrolytically charged particles). The hydrogen gas supplied to the anode side is split into ions due to the cathode action and gives off electrons:

2 H₂ → 4 H+ + 4 e–

These electrons are directed to the cathode via an external circuit, in which they perform electrical work. There they cause the oxygen to ionise in accordance with the following reaction equation:

O₂ + 4 e– → 2 O²–

Lastly, the free oxygen and hydrogen radicals combine with heat output to form electrically neutral water:

4 H+ + 2 O²– → 2 H₂O

The side on which the reaction gases accumulate and the type of ion transport through the electrolyte that is needed to close the circuit are dependent on the cell type (see figure 22).

Finally, the gas diffusion layer ensures a uniform distribution of the inflowing gases and reaction products along with the removal of electrons and process heat.

FUEL CELL TYPES
Fuel cells are categorised primarily by the type of electrolyte and the temperature at which the cell is operated. Five groups of fuel cells are distinguished by electrolyte type, and these range by temperature: low-temperature at less than approximately 100°C, medium-temperature above 100°C and below 200°C, and high-temperature above 500°C. The following section briefly presents the most important fuel cell types by electrolyte, along with their main areas of application, advantages and disadvantages, and the market development status.

Table 21 contains a summary of important performance parameters of fuel cells.

In general, the necessary purity of the hydrogen used decreases as the temperature rises – the lowest temperatures require the purest hydrogen. The efficiencies that can be achieved by the fuel cells are dependent among other things on the operation with air or pure oxygen.
In addition, the overall efficiency increases if the fuel cell is used not only for electricity generation but also for waste heat. The carbon monoxide and carbon dioxide emissions are significantly lower than those of those for internal combustion engines. Today, the service life of PEMFCs is approximately 5,000 operating hours which is sufficient for a travel distance of around 100,000 miles or 150,000 to 200,000 km (IEA 2015b).

The HT-PEMFC currently dominates the world market for fuel cells, in terms of both the number of installed systems and the output of the fuel cells (E4tech 2016; Chong and Harman 2011).

A further development of the low-temperature PEMFC is the high-temperature PEMFC. The HT-PEMFC uses a novel, acid-doped membrane and therefore does not need water for its conduction mechanism. This enables higher operating temperatures to be achieved (up to approximately 200 °C), while at the same time eliminating the complex water management process.

Furthermore, the carbon monoxide and carbon dioxide tolerance and the overall efficiency are higher – especially when it comes to waste heat utilisation. The use of heat and acid-resistant materials gives rise to higher production costs, however. In addition, the HT-PEMFC is technologically less mature than the LT-PEMFC. A special application of the PEMFC is the direct methanol fuel cell (DMFC). The DMFC operates in a similar temperature range (50 to 120 °C) to the LT-PEMFC. It can use the hydrogen contained in methanol (CH3OH) directly, and then benefits from the high storage density of methanol. However, the efficiency of the DMFC is relatively low (20%). It is mostly used in small devices. Overall, it plays only a minor role in the fuel cell market.

Phosphoric acid fuel cell (PAFC) The phosphoric acid fuel cell (PAFC) is categorised as a high-temperature fuel cell. A carbonate melt is used as the electrolyte. The operating temperature for MCFCs is 600 to 700 °C. Like PAFCs, MCFCs cover a broad output spectrum up to the MW range. The power density and flexibility of PAFCs are low. Their electrical efficiency is relatively low (40%), although by using waste heat higher overall efficiencies (80%) can be achieved than with AFCs and PEMFCs. PAFCs are less sensitive to carbon monoxide, but they require a higher noble metal loading.

PAFCs also require a complex water management process and have high material requirements. Because of their aggressive electrolyte, this cell type is less suitable for the small output range (in the building sector) and mobility applications; in the stationary sector, however, they have had a high degree of technological maturity for some time now. Further potential for cost reduction is therefore to be low, however. They are used mostly in large stationary fuel cells (such as small power plants), but in low numbers.

Molten carbonate fuel cell (MCFC) The molten carbonate fuel cell (MCFC) is the pioneer among stationary fuel cells (such as small power plants). It was first used at an early stage of space travel – for example for the on-board power supply for the Apollo mission in the 1960s. In its initial phase, the AFC was used almost exclusively for mobility applications, but it is also being tested in stationary applications.

The AFC is a low-temperature fuel cell. Key advantages include the rapid attainment of the low operating temperature and the compact design. The use of a simple electrolyte (potassium hydroxide solution) and low-cost catalysts (base metal) leads to low investment costs.

The main problem with the AFC is that it has a very low carbon dioxide tolerance and is therefore dependent on a supply of very pure gases, especially pure oxygen. Despite further developments such as the alkaline membrane fuel cell (AMFC), the AFC is inferior to the PEMFC in terms of output and durability.

Polymer electrolyte fuel cell (PEM) or proton exchange membrane fuel cell (PEMFC) The polymer electrolyte membrane is also a low-temperature (IT) fuel cell, which operates at temperatures of around 80 °C. Unlike the AFC, the PEMFC has a solid polymer membrane as the electrolyte. In contrast to the AFC, this avoids an elaborate preparation of the electrolyte. The PEMFC has a high power density and a small volume, making it especially suitable for mobility applications.

The noble metal catalyst (platinum) leads to high construction costs. Since the catalyst is also poisoned by sulphur and carbon monoxide, the PEMFC requires pure hydrogen. Unlike the AFC, however, it can operate with air rather than with pure oxygen. The LT-PEMFC additionally requires a complex water management process.

Of all the fuel cell types, PEMFC systems have the highest potential for cost reduction with regard to production volume. In the long-term, production costs of 30 $/kWe are considered to be achievable, comparable to those for internal combustion engine drivetrains. Today, the service life of PEMFCs is approximately 5,000 operating hours which is sufficient for a travel distance of around 100,000 miles or 150,000 to 200,000 km (IEA 2015b). The LT-PEMFC currently dominates the world market for fuel cells, in terms of both the number of installed systems and the output of the fuel cells (E4tech 2016; Chong and Harman 2011).

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21 FIVE TYPES OF FUEL CELL EXPLAINED

<table>
<thead>
<tr>
<th>Fuel cell type</th>
<th>Temperature range °C</th>
<th>Electrolyte</th>
<th>Electrical performance</th>
<th>Fuel</th>
<th>Oxidant</th>
<th>Efficiency ηel (%)</th>
<th>Investment costs USD/kWₑ</th>
<th>Life expectancy [h]</th>
<th>Market development</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFC</td>
<td>60 – 90</td>
<td>Potassium hydroxide</td>
<td>Up to 250 kW</td>
<td>H2</td>
<td>O2 (pure)</td>
<td>50 – 60 %</td>
<td>200 to 700</td>
<td>5,000 to 8,000</td>
<td>Established for decades, limited to specialised applications</td>
<td>Space travel, submarines</td>
</tr>
<tr>
<td>PEMFC</td>
<td>50 – 90 (LT) up to 180 (HT)</td>
<td>Polymer membrane</td>
<td>From 500 to 400 kW</td>
<td>H2, gas, syngas, biogas, methanol (external reforming)</td>
<td>O2</td>
<td>30 – 60 % (depending on size and application)</td>
<td>3,000 to 4,000 (stationary) – 500 (mobile)</td>
<td>60,000 (stationary) – 5,000 (mobile)</td>
<td>Early market/mature leading fuel cell type</td>
<td>Vehicle drivetrains, space travel, micro + blocktype CHP, backup power</td>
</tr>
<tr>
<td>PAFC</td>
<td>160 – 220</td>
<td>Phosphoric acid</td>
<td>Up to several 10 MW</td>
<td>H2, gas, syngas, biogas, methanol (external reforming)</td>
<td>O2</td>
<td>30 – 40 %</td>
<td>4,000 to 5,000</td>
<td>30,000 to 60,000</td>
<td>Mature (low volume)</td>
<td>Decentralised power generation, blocktype CHP</td>
</tr>
<tr>
<td>MCFC</td>
<td>600 – 700</td>
<td>Carbonate melt</td>
<td>From a couple of 100 kW to several MW</td>
<td>H2, gas, syngas, methanol (internal reforming)</td>
<td>O2</td>
<td>55 – 60 %</td>
<td>4,000 to 6,000</td>
<td>20,000 to 40,000</td>
<td>Early market/market introduction (especially for bigger plants)</td>
<td>Power plants (base load), CHP (process heat/steam)</td>
</tr>
<tr>
<td>SOFC</td>
<td>700 – 1,000</td>
<td>Solid ceramic oxide</td>
<td>From a couple of kW to several MW</td>
<td>H2, gas, syngas, methanol (internal reforming)</td>
<td>O2</td>
<td>50 – 70 %</td>
<td>3,000 to 4,000</td>
<td>up to 90,000</td>
<td>Mature (volumes rising)</td>
<td>Power plants, CHP (process heat/steam), micro + blocktype CHP</td>
</tr>
</tbody>
</table>

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Figure 22 shows the most important fuel cell types by points of origin of the reaction products on the anode or cathode side and the direction and type of ion transport through the electrolyte. Between them, the various fuel cell types cover a wide temperature range. Low operating temperatures allow for a dynamic load response, while high temperatures favour continuous loads. In addition, the electrolysis of the HT fuel cells are more resistant to impurities and to variations in fuel quality.

As combustion gases, either hydrogen is oxidised to water or carbon monoxide to carbon dioxide. In the PEMFC and PAFC the occurring water is drawn off at the cathode. In the case of the AFC and the high-temperature SOFC and MCFC cells, by contrast, the reaction products of the fuels supplied on the anode side leave the cell again on the same side. A special feature of the AFC is that it gives off product water via the electrolyte, causing the electrolyte to be diluted (Wendt/Plzak 1990).

Air or pure oxygen is supplied at the cathode as oxidant. Correspondingly, nitrogen and oxygen occur as residual gases at the cathode outlet. The fuel for the fuel cell can either be used directly in the fuel cell or prepared from various hydrogen-rich intermediates such as natural gas, methanol or synthesis gas via reforming. Depending on the operating temperature, reforming takes place internally or externally.

IN SUMMARY

Hydrogen is a highly versatile basic chemical. The most important material applications in industry are ammonia synthesis (fertilisers) and methanol synthesis. Another important use is the refining of oil and intermediates in refineries – called hydro-treating and hydrocracking – as well as the hydrogenation of vegetable oils in (bio) refineries.

Although it is possible to use hydrogen as an energy source in heat engines (such as the internal combustion engine), that rarely occurs now.

The fuel cell is now the leading conversion technology of hydrogen usage for energy purposes. Fuel cells have made huge technical progress in recent years and offer much higher electrical and overall efficiencies than thermal engines.

The world market for fuel cells is currently dominated by the low-temperature polymer electrolyte membrane fuel cell (PEMFC), which because of its power density, flexibility and cost reduction potential is most suitable for mobility purposes. The solid oxide fuel cell (SOFC) has developed into the second most important fuel cell type. This high-temperature fuel cell is used for continuous domestic energy or electricity supply and in the power plant sector.

5 STATIONARY ENERGY APPLICATIONS

The use of hydrogen for energy purposes occurs mainly in fuel cells. In 2015 and 2016 some 30,000 fuel cell systems were delivered worldwide, with a total generating capacity of approximately 200 MW (nominal electric output).

Around 80% of the fuel cell systems supplied and 60% of the fuel-cell capacities shipped were stationary applications (EETech 2016). Although transport applications are surpassing the stationary sector now, stationary fuel cells are still among the most important drivers of global market development for fuel cell technology (US DOE 2016).

Fuel cells generate both electricity and (by-product) heat. The common production and use of electricity and heat is also known as cogeneration or combined heat and power (CHP). In some cases only electricity generation is of interest, especially in the case of backup power units. Sometimes a relevant additional value is also seen in use of the by-product heat e.g. in the residential sector.

5.1 ELECTRICITY GENERATION

Stationary fuel cells can be used for decentralised power supply in off-grid areas. The market for backup power applications (BUP) is becoming increasingly important. Backup applications include firstly emergency power supply and secondly uninterruptible power supply (UPS).

Emergency generator sets are used for maintaining operation in the event of lengthy power outages. In such cases the switchover from the mains power supply is usually (briefly) interrupted.

Uninterruptible power supplies, on the other hand, are used to protect highly sensitive technical systems against mains supply fluctuations and short-term outages, so as to ensure continuous operation. Areas of use include in particular telecommunications and IT systems, such as radio towers or data processing centres.

In comparison to conventional thermal power plants, fuel cells have much higher electrical efficiencies of up to 60%, even for small plants. This is advantageous from an energetic perspective, since a lot of high-value electricity and little heat are produced.

In ongoing operation, fuel cell backups are characterised by the following advantages: long autonomous operation and service life, low maintenance costs due to the lack of moving parts, and quiet, (locally) emission-free electricity generation (FICTO 2014a; HMINWEV 2016).

The backup capacity of stationary fuel cells varies from a few kW to over 1 GWe. Fuel cells with low-wattage electrical outputs are often portable fuel cells, which offer weight advantages over rechargeable batteries and generators. A variety of different fuel cell types are used in the stationary sector, in some cases also for cooling. In addition to hydrogen, methanol, natural gas and liquefied petroleum gas are used as fuels (HMINWEV 2016).

5.2 DOMESTIC ENERGY

If, in addition to the generated electricity, the heat that is produced is also used, the process is referred to as combined heat and power (CHP). If such plants are used in the domestic heating sector, they are also described as micro-CHP or mini-CHP plants (Shell/BDH 2013) because of their smaller outputs.

CHP plants can be operated with two strategies: The plant covers either most of the electricity or of the heat demand. If electricity prices are high, an electricity-led mode of operation is appropriate. In this way the purchase of electricity from the grid can be minimised, or the generated
DOMESTIC ENERGY SUPPLY

FUEL CELL SYSTEM AS A PART OF being trialled or used in stationary fuel cells

pure hydrogen – from surplus renewable
temperatures, internal reforming is possible
natural gas infrastructure can be used.
cover peak heating requirements, are used.
with a higher space heating requirement,
For that reason, fuel cells are particularly
probably the biggest advantage of fuel cells over thermal power processes is the direct electrochemical conversion during electricity and heat generation and the associated higher electrical efficiency. In combined mode, i.e. electrical and thermal, fuel cells can achieve efficiencies of up to 95%. The electrical efficiency is up to 45%. Furthermore, fuel cell systems are characterised by high efficiencies over all load points, they are quiet, have low maintenance costs and operate (locally) emission-free (ASU 2016).

One disadvantage is that, because of higher purchase costs, fuel cell heating systems - without incentive schemes - are currently not yet economically viable as compared with condensing boilers. It can be assumed, however, that as numbers increase and as synergy effects with PEM fuel cells from automotive applications take hold, the purchase costs of fuel cell systems for domestic energy supply will continue to fall.

Specifically for domestic energy supply, there are large demonstration projects running in Germany (“Callux”) and in 12 EU member states (“ene field”), in which more than 1,500 PEM and SO fuel cell systems are operating in houses and apartment buildings. In the meantime, the first fuel cell systems for domestic energy supply are commercially available in Europe. Meanwhile, almost 200,000 gas-fuelled PEM and SO fuel cell systems for domestic energy supply have been installed and funded in Japan through the state “Ene-Farm” project; the Japanese government wants to have installed 1.4 million systems by 2020 and 5.3 million by 2030 (HMW-FEI 2016, Edelbach 2016).

Probably the biggest advantage of fuel cell systems is their high overall efficiency. Micro-CHP fuel cell heating systems achieve efficiencies of up to 95%, which is higher than any other conventional technology, including condensing boilers. In principle, the greater the spread between the electricity and gas price, the more cost-effective fuel cells become.

THE ECONOMICS OF A FUEL CELL HEATING SYSTEM

Using key data and own assumptions from the Shell BDH Domestic heating study (2013), this section analyses the economics of an investment in a micro-CHP fuel cell heating system for residential heating in comparison with a gas condensing boiler and an electric heat pump. For this purpose a simplified (total) cost of ownership (TCO) approach is applied. The cost of ownership analysis focuses on the investment cost for the heating equipment (including installation) and the costs of purchasing energy (for heat generation and electricity).

A reference building with a living area of approximately 150 m² is considered. In the reference building chosen, the heat required for domestic hot water and heating was previously generated by a low-temperature natural gas boiler. The specific energy consumption of 150 kWh per square metre for living space results in an annual natural gas consumption of 22,500 kWh. The annual domestic electricity consumption (4,000 kWh) is drawn from the general electricity grid. The assumed electricity price is 0.30 €/kWh, the natural gas price 0.065 €/kWh.

The low-temperature boiler which has been used for central heating so far is outdated by now. The owner needs to modernise the heating system and considers three options: a micro-CHP fuel cell heating system, a gas condensing boiler heating system and an electric heat pump. The life time of all three heating types is assumed to be 20 years.

Gas condensing boiler: The low-temperature gas boiler is replaced by a gas condensing boiler. The costs for this system and its installation amount to 20,000 €. The boiler runs on natural gas. For the replacement reduces the natural gas consumption to 20,100 kWh. As previously, all the domestic electricity consumption is drawn from the grid.

Heat pump: The low-temperature gas boiler is replaced by an electric air sourced heat pump (ASHP). The costs for the heat pump and its installation amount to 12,000 €. Operating the heat pump requires 7,200 kWh of heat pump electricity per year. The heat pump electricity tariff is 0.21 €/kWh. Again, all the domestic electricity consumed is drawn from the grid via the existing house connection.

Fuel cell heating system: The low-temperature gas boiler is replaced by a new micro-CHP fuel cell heating system. The costs for this system amount to 20,000 €. The fuel cell heating system consists of a fuel cell for simultaneous electricity and heat generation (electricity output 0.75 kW, heat output 1 kW). A natural gas condensing boiler that is additionally integrated into the heating system supplies the extra heat required to heat the building and for domestic hot water generation. The fuel cell heating system runs on natural gas. As electricity prices are high compared to the natural gas price, the most economic operating strategy of the fuel cell is to cover most of the electricity needed in the building; here 70% of the electricity generated by the fuel cell is consumed in the house. As such, less electricity has to be drawn from the grid. The electricity that is generated by the fuel cell and not consumed internally is fed into the grid.

In all three cases, the cost of ownership for energy are made up of the acquisition and installation costs for the heating system, the natural gas purchase costs, and the costs for domestic electricity supply via grid connection. For the fuel cell heating system this means that the costs for domestic electricity fall because of the consumption of the self-generated electricity. This reduction is (partially) offset by a higher natural gas consumption, however. Figure 24 shows the heating and electricity costs in EUR over time, i.e. the costs for acquiring each heating system (on the Y-axis intersection), and for the total operating costs (including acquisition cost) for three system options over 20 years of service (X-axis). The calculation does not take account of any grants for heating appliances or tax exemptions or feed-in remunerations for the electricity.

Owing to the low acquisition costs, the ownership costs for the gas condensing boiler are the lowest today. The acquisition costs for the fuel cell heating system are the highest. However, given the high proportion of self-generated electricity that is consumed, it has the lowest operating fuel and electricity costs. As such, the fuel cell heating system would be more cost-effective than an electric heat pump after just under 10 years of service. If the purchase costs of a fuel cell heating system were to fall, due to falling production costs or to direct subsidies as in Japan, for example, the fuel cell heating system would even be more cost-effective than the gas condensing boiler heating system after just a few years.

In principle, the greater the spread between the electricity and gas price and the higher the proportion of self-generated electricity that is used, the faster a fuel cell heating system pays off.

DOMESTIC ENERGY COSTS COMPARED
Hydrogen can serve as an energy source for mobility purposes. As such hydrogen can be used as a combustion fuel in the internal combustion engine, currently the dominant energy converter in road transport. However, the most important and promising combination for the future of the energy and mobility industry is the fuel cell as energy converter and hydrogen as energy source.

This chapter examines the technical foundations for the use of hydrogen and fuel cells in the mobility sector, looking at each means of transport. Of particular interest is the state of technology development or readiness, because an adequate technology readiness of fuel cell technology, while not sufficient in itself, is a necessary prerequisite for market success in the respective mobility application areas.

The technological potential for the fuel cell/hydrogen combination is assessed with respect to the requirements of each specific means of transport. Advantages and disadvantages of hydrogen and fuel cell transport applications in comparison with relevant alternative drive/fuel combinations are discussed.

The chapter concludes with a summary of technology readiness and the outlook for potential use of hydrogen (as a fuel) and fuel cells in transport.

### 6.1 Application Options and Means of Transport

The application options for hydrogen as a fuel for mobility can be differentiated firstly by the chemical form or conversion of hydrogen and secondly by the energy converter by means of which the energy stored in the hydrogen is made available.

**In direct use**, (pure) molecular hydrogen ($H_2$) is used by the transportation means directly, i.e. without further conversion, as an energy source. In this case hydrogen can be used both in internal combustion engines and in fuel cells (fuel cell systems).

**In indirect use**, hydrogen is used to produce final energy sources or is converted by means of additional conversion steps into gaseous or liquid hydrogen-containing fuels. Such PGS (Powerto-Gas) and PtL (Powerto-Liquids) fuels can then in turn be used in heat engines. Use in fuel cells would also be possible (in some cases), using a reformer, but it is not economically viable.

Until recently hydrogen was regarded as a promising alternative fuel for internal combustion engines. In principle, heat engines have multifuel capability, i.e. they can process different liquid and gaseous fuels. And hydrogen is highly suited to be used in internal combustion engines because of its material and combustion properties. Its broad ignition range and high flame velocity allow for improved combustion engine efficiencies. A further advantage of hydrogen as a fuel lies in its carbon-free combustion and significantly reduced air pollutant emissions in comparison to hydrocarbon fuels.

Up to about ten years ago, buses, vans and cars with hydrogen-powered internal combustion engines were being developed as prototypes and low-volume production vehicles. A number of different engine concepts and fuel mixing strategies were tested in this context. In the case of passenger cars and similar vehicles, only spark-ignition engines were used. In some cases they could even run on petrol too (bivalent engine). However, a disadvantage of using hydrogen in internal combustion engines is that, in contrast to fuel cell systems, the efficiency of hot hydrogen combustion is (fundamentally) no higher than that of conventionally operated petrol and diesel engines (Eichhäuser/Kiel 2014).

For that reason, and also because of the technical advances that have been made in mobile fuel cell technology, for all practical purposes only cold combustion is now being used in fuel cell systems in the mobility sector. The electrical energy generated from hydrogen in fuel cells can be used to drive motor vehicles or other means of transport. Moreover, small fuel cells can also supply electricity for ancillary components or auxiliary power units in vehicles or other means of transport. This applies in particular to larger means of transport such as ships or aircraft, which in some cases require considerable amounts of energy or electricity for ancillary components.

At the heart of the discussion are the state of development and prospects for hydrogen and fuel cell systems for powering transportation means. The exception is space travel, which can be regarded both historically and technically as having provided the impetus for the development of hydrogen as a fuel for transportation and fuel cell technology.

**SPACE TRAVEL**

The rocket propellant LH$_2$/LOX has been tried and tested extensively in space travel and has a high level of technical maturity. It has the great advantage that as well as being light, its high exit velocity of over 4000 m/s (in a vacuum) also generates a high specific impulse. Moreover, the combination of LH$_2$/LOX as a propellant is also environmentally advantageous, since it burns to form mostly water.

Owing to their advantages in space, LH$_2$/LOX are used primarily for the upper and main stages of rocket propulsion systems. Thus the main and upper stages of the European Ariane 5 launch vehicle carry around 185 t of LH$_2$/LOX in total, in order to deliver a payload of up to 20 or 10 t into a lower or higher orbit of the Earth (Arianespace 2016).

**SPACE TRAVEL AT A GLANCE**

- **Market maturity**: Established as a rocket propellant since the 1950s/1960s – with excellent reliability. Small “market” for launch vehicles with few applications.
- **Requirements**: Reliable, high-performance technology.
- **Advantages**: High specific impulse, clean combustion.
- **Disadvantages**: Cooling (cryogenic), large tank volumes, high pump capacity of fuel pumps.
- **Alternatives**: Liquid propellants (RP-1), gaseous propellants (methane) or solid propellants.

Less expensive alternatives to LH$_2$/LOX are solid fuels and liquid fuels – such as Rocket Propellant 1 (RP-1), a highly refined light middle distillate from the jet fuel family (JP-4). Liquid hydrocarbons (RP-1) or solid rocket propellants have a higher volumetric density than hydrogen, and this has a beneficial impact on the size of the fuel tank. They are also usually less expensive and easier to handle than hydrogen. However, their specific impulse is much lower and, unlike hydrogen in combination with oxygen, when they are burned they also produce greenhouse gases and air pollutants, some of which – in the case of solid fuel rockets – also contain toxic substances.

Other than as a rocket propellant, hydrogen has been used in space travel for more than forty years in fuel cells. In most cases these are alkaline fuel cells (AFCs), which run on the liquid hydrogen and oxygen that is carried anyway for propulsion purposes. They supply both electricity and heat as well as water for the on-board systems on spacecrafts.
In civil aviation, hydrogen-powered fuel cells are regarded as potential energy providers for aircraft as they have been in space travel for some time now. Thus, fuel cell modules can supply electricity to the aircraft electrical system as emergency generator sets or as an auxiliary power unit. More advanced concepts include combining the main engine and the nose wheel drive for aerial movements by commercial aircraft.

Since fuel cells produce electricity more efficiently than aircraft engines, in ground operations aviation fuel can be saved and emissions reduced. Furthermore, multifunctional fuel cells can contribute to the supply of water, air humidification and the inerting of fuels (Renoard-Valletta et al. 2012). The ideas and concepts for hydrogen in aviation extend to the support and/or complete drive of the flight operation. Individual jet engines may have occasionally been tested with hydrogen in the past. More recently, electric aviation has been boosted by a number of small demonstration aircraft, the size of unmanned drones, motor gliders or small sports aircraft with a mass of up to 1.5 t (DIR 2015). These miniature and small propeller aircraft were fitted with PEM fuel cells and lithium batteries for the drive. The custom-built electric planes were able to demonstrate the basic feasibility of hydrogen-powered fuel cells in flight operations over short distances.

The use of fuel cell technology as the sole or main drive and fuel for full-sized commercial aircraft in national and international air services is not yet in sight, however.

In the shipping industry, diesel engines are used almost exclusively today. Ocean-going vessels use either heavy fuel oil or marine diesel as fuel, while inland waterway vessels – within the EU for example – use commercial diesel fuel. To date the only relevant alternative drive option for the shipping industry is the use of liquefied natural gas (LNG) or compressed natural gas (CNG) to fuel ships.

As in aviation, fuel cells are currently being tested as energy providers for the onboard power supply. The functional capability of fuel cell modules has been tested successfully under maritime conditions (4ships 2016). Fuel cells work more efficiently than comparable diesel generator sets, in the partial load range in particular and through the possibility of combined heat and power generation. Air pollutant and noise emissions in ports can be reduced. In many cases the fuel cells are operated not with hydrogen but with other fuels, including methanol, natural gas or diesel fuel. These offer the advantages of greater availability, lower price and easier storage. They are converted into hydrogen with the aid of internal or external reformers.

The use of hydrogen-powered fuel cells for ship propulsion, by contrast, is still at an early design or trial phase – with applications in smaller passenger ships, ferries or recreational craft. The low-and high-temperature fuel cell (PEMFC) and the solid oxide fuel cell (SOFC) are seen as the most promising fuel cell types for nautical applications (EMSA 2017). As yet, however, no fuel cells have been scaled for and used on large merchant vessels.

Moreover, in comparison to the efficient, slower-running diesel engine, which runs on heavy fuel oil, the power train and fuel are still too expensive. In addition, international technical standards still need to be developed in order to use gaseous fuels (such as hydrogen) (Würsig/Marquardt 2016).

The main drive sources for rail vehicles are either diesel drives (diesel-electric, diesel-hydraulic) or all-electric. The energy intensity of electric rail vehicles is around half that of diesel rail vehicles (IEA/UIC 2015). An increase in line electrification in conjunction with a decarbonisation of railway electricity production would therefore be a possible energy and climate strategy for rail.

The proportion of electric traction is already high in some regions of the world. Electrification levels have reached 60 to 80% in Europe and Asia, and the average for EU member states is around 40%. Worldwide, however, the proportion of electrified railways is only around one-third. Over 50% of the railways in India are electrified, around 40% in China, a good 20% in Africa, but only a few percent in North America (IEA/UIC 2015).

In electric locomotives, motive power is supplied via stationary current conductors (overhead lines, conductor rails) and current collectors on the vehicles. However, for technical, economic or other reasons, not every railway line can be electrified. Especially on lines with a low transport volume, the high upfront investment that is needed for electrification of the lines can often not be justified. Moreover, overhead lines cannot be used for shunting if cranes are also in use for moving transport goods. In subsurface mining, by contrast, traction vehicles have to operate without air pollutants.

Rail vehicles that use hydrogen as an energy store and energy source can offer an additional alternative. Fuel cell-powered rail vehicles combine the advantage of pollutant-free operation with the advantage of low infrastructure costs, comparable with those for diesel operation.

The term hydrail as a short form of hydrogen rail has been coined to describe hydrogen-based rail vehicles. Hydrail applications can be reasonable in locations where an electric rail infrastructure cannot be built or where pollutant-free operation is required.

To date, two types of fuel cell-powered rail vehicles have been developed and tested: shunting locomotives and railcars for public (local) rail passenger transport. Heavy locomotives for (long-distance) rail freight transport are either all-electric, diesel-electric or diesel-hydraulic. The shunting locomotives are mostly either one-axle vehicles or conversions of diesel locomotives. Moreover, individual shunting locomotives have been fitted out and used for transport purposes below ground in the mining industry.

For light rail vehicles there is a funded test track for regional fuel cell trains in Northern Germany. 50 local trains are scheduled to be brought into service in various regions of Germany by 2021 (Eins & Young et al 2016). In addition, a fuel cell-powered train – also known as a hydrogen trolley or hydrolley – which has been developed in China operates on a tram line in the Chinese coastal city of Qingdao. Other tram lines are at the planning stage.

Light passenger rail vehicles frequently cover only short distances each day, for which large energy stores are not required. The expensive combination of fuel cell and on-board hydrogen tank can pay off, if the costs of setting up and maintaining overhead lines are avoided. In the long-term, it might also be possible for parts of the infrastructure to be shared with fuel cell buses.
## Requirements
- Sufficient and reliable hydrogen supply.

## Advantages
- Lower infrastructure costs (no overhead lines/conductor rails); (locally) emission-free operation, dependent on hydrogen production.

## Disadvantages
- Expensive drive system; additional tank space.

## Alternatives
- Diesel (electric/hydraulic) with diesel or PX fuels; electric traction.

### INDUSTRIAL TRUCKS (FORKLIFTS/TOW TRUCKS)
Industrial trucks are another area of use for fuel cell technology. Industrial trucks can run on the ground or on a rail system. The most common types are forklifts and tow trucks, which are used in intralogistics, i.e. for handling flows of materials within a company. In many cases industrial trucks operate in enclosed areas, but they are also used outdoors – at airports for example. Worldwide more than 10 million industrial trucks are used every day, and the fleet is growing (Kühnert/Michelli 2015).

Industrial trucks are available with both electric drives and internal combustion engines. In the case of electric drives for indoor use, lead-acid batteries are still widely used. Internal combustion engine industrial trucks are often low-emission gas vehicles (liquefied petroleum gas) or petrol vehicles.

Fuel cell industrial trucks are especially suitable for indoor operation, because they produce no local pollutant emissions and only low noise emissions. Fuel cell vehicles have advantages over battery-operated industrial trucks in terms of refueling. Instead of having to replace the battery, the trucks can be refueled within two to three minutes. They take up less space and are cheaper to maintain and repair. Fuel cell industrial trucks allow for uninterrupted use and are therefore particularly suitable for multi-shift operation in material handling (FCTO 2014b). In the case of larger industrial trucks in multi-shift operation, (moderate) cost reductions can be achieved in comparison to battery technology, and productivity in material handling can also be increased (NREL 2013a).

In Europe there are around 140 fuel cell industrial trucks in operation at present. In order to drive commercialisation forward, a further 200 fuel cell-operated material handling vehicles are set to be brought into circulation in small fleets at 10 to 20 selected locations as part of the MyLIFT Europe project. In Asia there are as yet only prototypes in Japan (FCTO 2015; Landinger 2016).

### INDUSTRIAL TRUCKS AT A GLANCE

<table>
<thead>
<tr>
<th>Market maturity</th>
<th>To date, demonstration projects for light rail vehicles (based on bus technology). Various shunting locomotives as pilot projects/one-off vehicles.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Requirements</td>
<td>Hydrogen supply (in some cases outdoor) for larger vehicle fleets, multi-shift use.</td>
</tr>
<tr>
<td>Advantages</td>
<td>Continuous operation, high material handling productivity, (locally) emission-free operation.</td>
</tr>
<tr>
<td>Disadvantages</td>
<td>Lightweight drive, requires extra weights.</td>
</tr>
<tr>
<td>Alternatives</td>
<td>Battery electric vehicles (indoors); gas, petrol, diesel (outdoors).</td>
</tr>
</tbody>
</table>

### INDUSTRIAL TRUCKS (FORKLIFTS/TOW TRUCKS)

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Sufficient and reliable hydrogen supply.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternatives</td>
<td>Electric drive system; additional tank space.</td>
</tr>
</tbody>
</table>

### Market maturity

- Technology tried and tested in numerous small fleets worldwide (Europe, North America, Asia), larger projects with several hundred buses at the planning stage; currently only in publicly funded transport projects, studies on commercial use (CFCP 2013; RB 2015).

### Requirements

- Flexible, reliable use in scheduled services with short downtimes (for refueling/charging); ideally no space and weight restrictions for passenger transport.

### Advantages

- Range 300 to 450 km, no public infrastructure needed for municipal buses, range still too short for coaches; no air pollutants, low noise emissions, little additional weight from hydrogen tanks.

### Disadvantages

- Vehicles still more expensive than the reference technology of diesel buses.

### Alternatives

- Gas buses, diesel hybrid buses, electric buses.

### BUSSES AT A GLANCE

<table>
<thead>
<tr>
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</tr>
<tr>
<td>Alternative</td>
<td>Gas buses, diesel hybrid buses, electric buses.</td>
</tr>
</tbody>
</table>

### BUSES

In terms of road transport, buses in the public transport network are the most thoroughly tested area of application for hydrogen and fuel cells. Since the early 1990s, several hundred buses have been and are being operated with hydrogen worldwide – predominantly in North America, Europe and increasingly in Asia. ALMOST ALL LORRIES AND LIGHT COMMERCIAL VEHICLES

Almost all lorries are fitted with diesel engines; this is especially true of the heavy goods vehicles used for long-distance road haulage. Alternative drives and fuels - mostly gas vehicles (CNG and LPG) - are only used for light commercial vehicles, and even then only in small numbers as yet. Electric drives have so far been unable to achieve significant numbers in lorries because of the weight and volume of the batteries needed to provide the necessary range reduces the payload to an unacceptable level. However, a gradual increase in hybridisation/electrification is anticipated in the future for light commercial vehicles and small lorries (Shell 2016). In terms of lorries, in California and Germany there are as yet just a few publicly funded...
vehicles which draw their drive energy from hydrogen-powered fuel cells.

In principle, the wealth of experience and concepts in bus applications can be drawn on regarding the use of fuel cells goods vehicles. The prototypes are mostly light to medium lorries, which because of their low noise emissions and absence of pollutants are intended for use in urban delivery services. As a rule they are generally battery electric vehicles, which have been fitted with a fuel cell as a range extender.

The use of fuel cells in long-distance road haulage, i.e. for 40-ton trucks in the EU or class 7/8 trucks in the USA, is further behind. Meanwhile, concepts or prototypes for heavier lorries are available. However, vehicles of the 300 to 350 kW output class would still need to be tested in long-term use over long distances. Pre-requisites for use in long-distance road haulage are considered to be the minimising of losses in payload (and volume), competitive fuel prices, the maximum possible range and an adequate refuelling station infrastructure (ABB 2015; Wieschal et al. 2016).

Finally, the use of fuel cells to supply auxiliary equipment with electricity is also discussed. Here reformers convert diesel fuel into hydrogen, which is used efficiently and with few or no air pollutants by appropriately dimensioned fuel cells to operate refrigeration systems and the like.

LORRIES AND LIGHT COMMERCIAL VEHICLES AT A GLANCE

Market maturity: Vehicles mostly in the USA (around 50), with individual examples in Germany/EU. Concepts and prototypes primarily for smaller lorries in urban areas with air quality issues, but also first concepts/prototypes for heavy goods vehicles.

Requirements: Space-saving hydrogen storage; reliable supply; reduction in total cost of ownership.

Advantages: Higher efficiency, no air pollutants, low noise emissions.

Disadvantages: Expensive drive technology/fuel, still shorter range than diesel; low density of refuelling stations.

Alternatives: Diesel vehicles, LNG/CNG and battery-electric commercial vehicles (BEVs).

MOTORCYCLES

Light motorcycles were an early commercial application of fuel cell technology in motorised private transport. In emerging and developing economies, motor scooters and small motorcycles are an indicator of an increase in motorisation. However, two-stroke or four-stroke motorcycle engines running on fossil fuels lead to increased air and pollutant emissions in conurbations. Electric scooters and motorcycles, by contrast, offer the advantage of zero-pollutant and low noise emission travel. In the past, however, they suffered from the low storage density and hence range of batteries. Due to technical advances in battery technology, however, the typical daily distances travelled in cities can now often be covered.

The last two decades saw a succession of two-wheeled prototypes equipped with a variety of fuel cell types and storage systems. The commercial implementation of fuel cell motorcycles foundered, however, partly because of the higher purchase/running costs for the fuel cell technology and the inadequate hydrogen supply infrastructure (Wing 2012). In addition, battery technology can cover the moderate performance requirements for electric motorcycles and mopeds in urban commuter traffic. As a result there are now only a few current prototypes, including a motor scooter with pan-European approval as a production vehicle (Suzuki 2011).

Motorcycles with internal combustion engines, e-bikes and e-scooters.

6.2 TECHNOLOGY READINESS

Finally, the degree of technical readiness or the state of development of hydrogen-powered drives - mostly fuel cell vehicles - is assessed. Hydrogen-powered vehicles are categorised by reference to the Technology Readiness Levels (TRL) devised by NASA (NASA 1995; DOD 2011; ISO 2013). The Technology Readiness levels range from the basic description of the operating principle [TRL 1] through a proof of concept [TRL 3] up to TRL 9 [technology established in the market]. In almost all the vehicle categories considered, there are at least experimental setups or [small] prototypes which have been tested - if not necessarily to scale - in their operational environment with hydrogen and/or fuel cell technology. For that reason, the rest of this section concentrates only on TRL levels 5/6 (experimental setup in operational environment/prototype) upwards. The ultimate objective of technological development is TRL 9, a technology established in the market - like internal combustion engine drives in road transport. The prerequisites for this is an approved, functioning technology (TRL 8).
What is the technological maturity of the individual means of transport in terms of hydrogen and fuel cells today?

The highest Technological Readiness Levels, TRL 8 or 9, are achieved by fuel cell industrial trucks, for which extensive experience in the field is already available in large numbers, especially in North America. Cars are at TRL 8 and buses at TRL 7 to 8. The longest and most extensive operational experience is available for heavy goods vehicles, but it is a small niche market with few applications over time. Nonetheless, the technology itself should be categorised at TRL 8.

Technology readiness is an important prerequisite for the commercial success of new technologies. However, a high level of technology readiness, while a necessary condition, is not sufficient in itself for market success. Depending on the technology user, there are other important factors affecting the purchase, maintenance or use of a means of transport with a specific drive/fuel combination.


definition of technology readiness levels

<table>
<thead>
<tr>
<th>TRL</th>
<th>Definition of Technology Readiness Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Conceptual design - technology concept demonstrated</td>
</tr>
<tr>
<td>2</td>
<td>Experimental setup - technology demonstrator operated</td>
</tr>
<tr>
<td>3</td>
<td>Prototype in operational environment - demonstration almost to scale in the operational environment</td>
</tr>
<tr>
<td>4</td>
<td>Prototype in use - demonstration of key technology elements functional in area of use - product</td>
</tr>
<tr>
<td>5</td>
<td>Qualified system with proof of functional capability in area of use - product</td>
</tr>
<tr>
<td>6</td>
<td>Qualified system with proof of successful use - product</td>
</tr>
</tbody>
</table>

For heavy goods vehicles, first concepts are available. The use of fuel cell technology for ship and aircraft propulsion systems is currently at TRL 5 to TRL 6, with only small prototypes to date. There are no equivalent concepts yet for merchant ships and commercial aircraft. Fuel cells are successfully used as auxiliary power units (APUs); however, these are still one-off products for experimental purposes (TRL 6).

Lastly, rocket propulsion systems are difficult to categorise. Hydrogen-fuelled rockets have been used in space travel for decades, but it is a small niche market with few applications over time. Nonetheless, the technology itself should be categorised at TRL 8.

SPACE TRAVEL

The most important advantages of hydrogen and fuel cells in road transport are the higher efficiency of the energy converter, zero-pollutant operation (in fuel cells) and functionality comparable to established IC engines.

IN SUMMARY

Space travel provided the impetus for the development of hydrogen as a transport fuel and of fuel cell technology. In the transport sector, hydrogen is now used almost exclusively in fuel cells.

Hydrogen fuel cell systems are suitable for virtually all means of transport. Passenger cars, buses and material handling vehicles have technically reached series-production readiness, and are not far off that point, or are already in the early stages of commercialisation. Fuel cell passenger cars now offer the same features as those powered by internal combustion engines.

There are many factors determining the choice and operation of a vehicle. They include technical parameters (such as range or engine power), ecological parameters (such as emissions), regulatory parameters (such as usage restrictions/driving bans) or qualitative parameters (such as comfort or prestige). An important factor in deciding whether to buy or keep a car is economic in nature, i.e. the costs involved. These can include the (substantial) purchase costs of the vehicle, running costs, or costs relating to a specific mileage or transport capacity. This chapter looks at the economics of hydrogen-powered fuel cell passenger cars and compares fuel cell electric vehicles (FCEV) with competing drive/fuel combinations – namely petrol cars, petrol hybrids and battery electric passenger cars.

An analysis tool to assess the economic viability of different fuel-drive-train combinations is the total cost of ownership (TCO) approach as established in commercial road transport. TCO analysis takes account of all the direct and indirect costs of vehicle ownership for the purposes of providing a desired passenger or goods transport service.

The fixed TCO costs include the acquisition costs for a car, i.e. the purchase price (usually for the basic version of a vehicle) or, if financing is used, the instalment payments plus interest. If the car is to be sold again, the depreciation over the desired ownership period or the trade-in value must also be estimated. Vehicle tax and car insurance are included in the fixed costs.

In addition, workshop costs (for maintenance and wear-and-tear repairs) must be taken into account (ADAC 2016). Furthermore, assumptions have to be made about key cost items – regarding insurance tariff or depreciation for example. Finally, the running TCO costs include spending on fuel or energy and consumables.

The TCO estimate is complex and is appropriate primarily for rational economic operators. For the analysis of financial decisions of private households, however, a simple comparison of the most important differentiating cost items is usually sufficient. The key cost differentiators are the purchase price of the vehicle and the fuel costs for its operation. If the ownership costs for different drive types are similar, they are assumed to have little influence on purchase and operation decisions; if they differ significantly, the ownership costs can
tip the balance for or against a drive/fuel combination. A simplified ownership cost comparison for a fuel cell passenger car is set out below. The vehicle in question is a C segment (compact class/lower medium) passenger car, Europe’s bestselling car class. The fuel cell electric vehicle should be a fuel cell dominant system, rather than having a fuel cell range extender fitted. It is assumed that low-pollutant, hybrid petrol car concepts will be the competing technology for zero-emission vehicles in the medium term. Therefore, the fuel cell passenger car is compared with an internal combustion engine C-segment car – both a petrol-only and a hybrid petrol vehicle.

In addition, fuel cell passenger cars are compared with battery electric vehicles, since they are the only relevant alternative in the zero-emission drives sector. The ownership cost analysis considers passenger car models of the 2020s. It should be noted that under the EU directive to reduce CO2 emissions from new passenger cars (333/2014/EC), (European) vehicle manufacturers are required to reduce the specific CO2 emissions from their newly registered vehicles to an average of just 95 g CO2/km (based on the New European Driving Cycle). Similar CO2 limits apply in Korea and the USA with maximum permissible values of 97 and 88 g CO2/km with effect from 2020 and 2025 (ICT 2014a), while the regulations in Japan and China are somewhat less strict. In order for a petrol car to emit only 95 g CO2/km it must have a fuel consumption amounting to around 4 l/100 km. That would be a challenge for a simple petrol C-segment car, but not for a hybrid petrol car.

The assumptions regarding vehicle equipment and (standard) fuel consumption are based on (ECJ 2013) for “2020 plus” category vehicles, those passenger cars are already characterised by high efficiency and low fuel consumption figures. The standard fuel consumption figures were converted into real fuel consumption figures mainly by reference to (ICT 2016) and sources cited therein. Passenger car purchase costs by drive type up to 2030 were taken from an ambitious climate protection scenario (2DS) in (IEA 2015b). The fuel prices for the alternative drive systems were varied in order to estimate sensitivities. The assumed values are not future projections but only assumptions for the purposes of the ownership cost analysis.

The ownership costs for each drive/fuel cost combination are compared with one another in an XY chart (figures 27 and 28). The X-axis shows the total mileage over the lifetime of the passenger car, while the Y-axis shows the ownership costs (purchase and fuel/energy costs) accrued in total over a given mileage. The point where an ownership cost curve intersects with the Y-axis indicates the purchase costs for a given passenger car drive/fuel configuration. The gradient of the ownership cost curve reflects the fuel or energy costs for a car drive type as a function of mileage, based on European energy and fuel prices.

It should be noted that the fuel or energy costs for operating the vehicle are determined not only by the fuel prices (in €/litre or MJ) but also by the efficiency of the car drive in question. Concerning the cost per unit of energy in €/MJ hydrogen – like electricity – is more expensive than fossil fuels today (petrol at 1.5 €/l, figure 26). However, since both fuel cell electric vehicles and battery electric vehicles are more efficient than petrol vehicles, their MJ/km consumption is lower. At European fuel

### FUEL CELL CONCEPTS FOR PASSENGER CARS

For automotive applications, low-temperature polymer electrolyte membrane fuel cells are now used almost exclusively. In the PEM fuel cell, hydrogen is converted with oxygen to water. The technology has a high degree of maturity and is characterised by a simple setup, fast response to load changes, good cold start properties and a high power density (Göpfert/Michl 2015).

Fuel cell stacks are formed from several hundred cells in order to build a vehicle powertrain. Power outputs of 100 kW or more can be achieved in this way. The catalytic coating of the electrodes with platinum materials is a costly feature of PEM fuel cells. In order to lower costs, the aim of fuel cell production is more can be achieved in this way. The catalytic coating of the electrodes with platinum materials is a costly feature of PEM fuel cells. In order to lower costs, the aim of fuel cell production is PEM fuel cell operating temperature of 80 to 85°C cannot be exceeded significantly, additional electrical power for cooling the stack is needed. Moreover, operation in extremely hot regions represents a technical challenge (Reif 2010).

In addition to the fuel cell stack, a fuel cell vehicle also has a traction battery (usually Lithium or nickel-metal hydride rechargeable batteries). Electrical energy from the fuel cell or from regenerative operation of the powertrain (re recuperation) can be temporarily stored in this battery. The traction battery also serves to cover short-term power peaks. The traction battery is operated at a much higher voltage than the current vehicle electrical system (12 V).

The electric powertrain of fuel cell electric vehicles, i.e. electric motors and power electronics, is no different from the drive for battery electric vehicles. If the fuel cell stacks feed electrical energy directly into the electric motor and as when required, this is described as a fuel cell dominant system. If the fuel cell stack only supplies the traction battery, which in turn is the sole energy source cited therein. Passenger car purchase costs by drive type up to 2030 were taken from an ambitious climate protection scenario (2DS) in (IEA 2015b). The fuel prices for the alternative drive systems were varied in order to estimate sensitivities. The assumed values are not future projections but only assumptions for the purposes of the ownership cost analysis.

The ownership costs for each drive/fuel cost combination are compared with one another in an XY chart (figures 27 and 28). The X-axis shows the total mileage over the lifetime of the passenger car, while the Y-axis shows the ownership costs (purchase and fuel/energy costs) accrued in total over a given mileage. The point where an ownership cost curve intersects with the Y-axis indicates the purchase costs for a given passenger car drive/fuel configuration. The gradient of the ownership cost curve reflects the fuel or energy costs for a car drive type as a function of mileage, based on European energy and fuel prices.

It should be noted that the fuel or energy costs for operating the vehicle are determined not only by the fuel prices (in €/litre or MJ) but also by the efficiency of the car drive in question. Concerning the cost per unit of energy in €/MJ, hydrogen – like electricity – is more expensive than fossil fuels today (petrol at 1.5 €/l, figure 26). However, since both fuel cell electric vehicles and battery electric vehicles are more efficient than petrol vehicles, their MJ/km consumption is lower. At European fuel prices.

### FUEL CELL DOMINANT SYSTEM

[Diagram showing the components of a fuel cell dominant system including fuel cell, hydrogen tank, electric motor, converter, and battery.]

### BEV WITH RANGE EXTENDER

[Diagram showing the components of a battery electric vehicle with range extender including battery, electric motor, converter, and petrol engine.]

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### CAR OWNERSHIP COSTS

#### 26 FUEL COSTS AT EUROPEAN FUEL PRICES, PASSENGER CARS 2020+

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Price</th>
<th>Total Mileage (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen</td>
<td>€/kg</td>
<td>€/100 km</td>
</tr>
<tr>
<td>Petrol</td>
<td>€/l</td>
<td>€/100 km</td>
</tr>
<tr>
<td>Electricity</td>
<td>€/kWh</td>
<td>€/100 km</td>
</tr>
</tbody>
</table>

#### 27 OWNERSHIP COSTS COMPARED: FCEV AND PETROL POWERED

<table>
<thead>
<tr>
<th>Mileage (km)</th>
<th>FCEV 2020+</th>
<th>Petrol 2020+</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000</td>
<td>80,000 €</td>
<td>80,000 €</td>
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<td>30,000</td>
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<tr>
<td>80,000</td>
<td>200,000 €</td>
<td>200,000 €</td>
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</tbody>
</table>

#### 28 OWNERSHIP COSTS COMPARED: FCEV AND BEV

<table>
<thead>
<tr>
<th>Mileage (km)</th>
<th>FCEV 2020+</th>
<th>BEV 2020+</th>
</tr>
</thead>
<tbody>
<tr>
<td>20,000</td>
<td>80,000 €</td>
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An important factor in deciding whether to buy or keep a passenger car is the ownership costs involved. These include the car purchase costs, running costs, or ownership costs relating to a microwave or transport capacity.

At today’s cost structures fuel cell passenger cars are not yet competitive. But in an ambitious climate scenario involving rapid technological advances and market development, automotive fuel cell technology would quickly become much more cost-effective. In addition, production costs for hydrogen (from renewables) could fall in the medium to long term, and – with lower hydrogen infrastructure costs – it could be distributed more cheaply as a fuel.

At the same time, internal combustion drive systems are becoming more expensive, and in urban and metropolitan areas they are often subject to local usage restrictions as a result of stricter air quality regulations. As a consequence, locally emissions-free fuel cell electric vehicles powered by hydrogen are becoming increasingly attractive in comparison to cars with an internal combustion engine, and not on cost grounds alone.

If the gap between the purchase costs of fuel cell cars and battery electric cars can be closed as production numbers increase, fuel cell cars can also offer an alternative to locally emission-free battery electric vehicles. That is because, with comparable ownership costs, fuel cell electric vehicles offer further advantages over battery electric vehicles, such as greater comfort, longer range and shorter charging times. By contrast, if battery electric vehicles are improved in terms of comfort, range or charging time, they will become more expensive and will lose any economic advantages they may have over fuel cell electric vehicles.

FCEVs versus Petrol Cars

Until now, FCEVs have still not been sufficiently attractive to many consumers in cost terms because of their high price purchase in comparison to petrol and diesel cars. In the future, cars driven by an internal combustion engine will be more expensive – in part because of higher costs for drivetrain technology (such as direct injection, hybrid systems) and because of more complex exhaust emission control systems.

On the other hand, fuel cell electric vehicles would become less expensive because of technological development, learning curve effects and effects of scale in production (IEA 2015b). The hydrogen consumer prices could also fall as a result of a more cost-efficient hydrogen supply and retail infrastructure. If the purchase price for a fuel cell electric vehicle were to fall by half, combined with a moderate reduction in hydrogen refuelling station prices, the ownership costs for an FCEV would be lower than those for a petrol car after just 50,000 to 60,000 km. With virtual cost parity, non-economic advantages – such as the possibility of locally emission-free driving in cities – could tip the balance in favour of purchasing an FCEV.

In addition, fossil fuels could also become relatively more expensive, and this would likewise increase the economic attractiveness of an FCEV as compared to a petrol car. However, a more efficient hybrid petrol car could (partially) compensate for the higher fuel prices. By contrast, lower fossil fuel prices – which prevail for example in the USA or which could be induced by lower crude oil prices in a 2°C climate action scenario (IEA 2016b) – may diminish the economic advantage of an FCEV in terms of mileage-dependent fuel costs. Because of the lower specific hydrogen consumption (in MJ/km), variations in the hydrogen retail price have less of an impact in the ownership cost comparison with internal combustion drive systems than changes in fossil fuel prices.

FCEVs versus BEVs

Battery electric vehicles currently have a head start of several years over fuel cell electric vehicles in terms of technology and market development. This lead is expressed in a greater variety of battery electric vehicles and in more established and also lower purchase prices. Furthermore, all electric drives are even more efficient than fuel cell electric vehicles.

The extent to which BEV energy costs per kilometre are higher or lower than those for FCEVs depends on the electricity prices. Depending on the purchase category – domestic electricity versus offpeak or preferential electricity tariff – the retail prices for electricity can fluctuate. High domestic electricity prices make running battery electric cars more expensive, while low electricity tariffs make it cheaper.

Overall, however, the distance-based energy costs of both electric variants are still similar, and this is reflected in similar gradients of the ownership cost curves.

If the gap in purchase costs between FCEVs and BEVs could be more or less closed, the costs for fuel cell electric vehicles and battery vehicles (per vehicle kilometre) would be very similar. Under these circumstances, because of advantages in terms of comfort, range and charging time, some potential buyers would probably be inclined to opt for fuel cell electric vehicles. Conversely, improving the range and charging time performance of BEVs would increase their purchase costs, thereby reducing their economic advantage.

IN SUMMARY

An important factor in deciding whether to buy or keep a passenger car is the ownership costs involved. These include the car purchase costs, running costs, or ownership costs relating to a microwave or transport capacity. At today’s cost structures fuel cell passenger cars are not yet competitive. But in an ambitious climate scenario involving rapid technological advances and market development, automotive fuel cell technology would quickly become much more cost-effective. In addition, production costs for hydrogen (from renewables) could fall in the medium to long term, and – with lower hydrogen infrastructure costs – it could be distributed more cheaply as a fuel. At the same time, internal combustion drive systems are becoming more expensive, and in urban and metropolitan areas they are often subject to local usage restrictions as a result of stricter air quality regulations. As a consequence, locally emissions-free fuel cell electric vehicles powered by hydrogen are becoming increasingly attractive in comparison to cars with an internal combustion engine, and not on cost grounds alone.

If the gap between the purchase costs of fuel cell cars and battery electric cars can be closed as production numbers increase, fuel cell cars can also offer an alternative to locally emission-free battery electric vehicles. That is because, with comparable ownership costs, fuel cell electric vehicles offer further advantages over battery electric vehicles, such as greater comfort, longer range and shorter charging times. By contrast, if battery electric vehicles are improved in terms of comfort, range or charging time, they will become more expensive and will lose any economic advantages they may have over fuel cell electric vehicles.

The development of a hydrogen economy for the automotive industry will require a new infrastructure. This infrastructure will consist of fuel production, storage and distribution facilities. In the transport sector, the new hydrogen infrastructure will also have to provide a hydrogen supply network for fuel electric vehicle. This chapter looks at the current state and expansion of the (public) hydrogen infrastructure for road transport. It then assesses the building blocks for a future hydrogen infrastructure, including hydrogen refuelling station concepts and refuelling station technology, possible supply and distribution pathways. Finally, the economics of a future hydrogen infrastructure for road transport are discussed.

8 REFUELLING INFRASTRUCTURE

The geographical distribution of hydrogen stations largely corresponds to the number of hydrogen-fuelled motor vehicles. Most of the approximately 4,200 fuel cell electric vehicles that were registered at the beginning of 2017 are located either in Japan or in the USA – with over 90% of the vehicles in the USA being concentrated in California. Also more than 90% of the fuel cell vehicles are passenger cars, the second biggest vehicle class being fuel cell electric buses (HyArc 2017).

While only a moderate number of new hydrogen refuelling stations were built over the last decade, the number of new stations opening each year has risen markedly in recent years. As of the beginning of 2017, a further 140 refuelling stations worldwide were in planning, under construction or in commissioning. At the same time, the start of commercialisation is leading to a growth in the fuel cell electric vehicle fleet. As a consequence, significant variations or differences in the statistics for hydrogen refuelling stations and for fuel cell electric vehicles may occur.

8.1 STATIONS AND VEHICLES

According to a recent survey (HyArc 2017), at the beginning of 2017 there are around 280 active hydrogen refuelling stations worldwide. According to this survey, Japan has the largest number of refuelling stations, with 91, followed by the USA with 61 stations, the majority of which (30) are in California (CaCFP 2017). In Europe, Western Europe and in particular Germany is leading with 37 stations. One fourth of the hydrogen refuelling stations are non-public (HyArc 2017).

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A hydrogen refuelling station can also be established and stored in a liquid tank. If the fuel is delivered by compressed hydrogen gas, the hydrogen is stored in the high-pressure storage tank, i.e. 350 or 700 bar. Another important element is the user interface, which contains various displays showing pressure, fill level or measured quantity.

Finally, the hydrogen can be produced either locally at the refuelling station or centrally in another location and then delivered. In the case of decentralised hydrogen production at the refuelling station, the production concept has to be decided. The options are a reformer for producing hydrogen from natural gas or (biomethane) or an electrolyser for producing hydrogen from (renewable) electricity.

8.4 STANDARDS
To ensure safe operation, a large number of technical standards must be adhered to when building and operating hydrogen refuelling stations. Work is still ongoing on hydrogen-specific codes and standards for the automotive hydrogen economy, since in some cases regulations not designed for hydrogen make building and operating refuelling stations more difficult and more expensive [HMF 2013]. Technical standards published by the International Organization for Standardization (ISO) or the Society of Automotive Engineers (SAE) specify concrete requirements for the hydrogen refuelling station infrastructure.

The most important technical standard is ISO 19980 (Gas-powered Hydrogen Fuelling Stations). Other ISO standards are relevant for construction and also operation. For instance, the EU alternative fuels infrastructure directive (AFID) or ISO 14687-2 for PEM fuel cell electric vehicles (FP Council 2014a).

Hydrogen fuelling must take place within hydrogen-storage system limits. The Worldwide Hydrogen Fueling Protocol SAE J2601 fuels all hydrogen storage systems quickly to a high state of charge (SOC) without violating the storage system operating limits of internal tank temperature or pressure. SAE J2799 was adopted as a standard in 2014. SAE J2601 (in combination with SAE J2799) is being used as a basis for fuelling light duty fuel cell electric vehicles with 350 or 700 bar worldwide. SAE J2601 defines pressure tolerances and temperature windows for safe and convenient hydrogen refuelling. Apart from light duty vehicles, SAE J2601 also covers heavy duty vehicles and forklifts.

8.5 REFUELLING STATION SIZES
Regardless of the way in which hydrogen is supplied and delivered, refuelling stations can be differentiated by size. Mobility (HMF 2010) classifies four sizes of refuelling stations, "very small (XS)", "small (S)", "medium (M)" and "large (L)", depending on the number of refuelling operations or the volume of hydrogen sold (table 31). In principle, Xs stations with even higher output data are also conceivable, no stations of this size are expected for the moment. The XS refuelling stations are visually research stations, in which economic optimisation is not a priority. The commercialisation of hydrogen refuelling stations only starts with size S or M.

The hydrogen station equipment has to be sized accurately for the station. A modular design enables smaller hydrogen refuelling stations to be expanded into larger ones if the hydrogen demand also increases in line with rising vehicle numbers. Nonetheless, over the course of the development of hydrogen refuelling stations, structural changes may occur that require a shift to a different refuelling station concept. To ensure a high capacity utilisation of the refuelling station and hence to achieve as steady a throughput as possible, hydrogen should be delivered in accordance with need. If an hydrogen refuelling station is serving bus fleets used in local public transport, its throughput rises significantly. As delivery volumes rise, the supply of liquid hydrogen (station size 1 or X) will become economically viable.
The space required for delivering, storing and dispensing hydrogen at the refuelling station is a factor that must be considered, especially in inner city areas. Of the various supply concepts, on-site production requires the most space, since the electrolyser or reformer is located on the refuelling station premises. At the same time, the storage requirement is lower, since hydrogen can be produced to a greater extent on demand. On the other hand, optimisation work has already reduced the space needed for the hydrogen handling equipment. Whereas 5 years ago, hydrogen facilities were still housed in 400-cubic-meter containers (corresponding to 12 m³), smaller containers measuring 11 feet (3.3 m) are today sufficiently large.

8.6 DISTRIBUTION

In terms of hydrogen supply, there are two different options available for refuelling stations: the delivery of externally produced hydrogen to the stations, or decentralisation of production on-site. Currently, most refuelling stations are supplied with centrally produced hydrogen (HyARC 2017). When it comes to on-site hydrogen production at the refuelling stations that are operating around the world, electrolysis ranks ahead of the reforming of gaseous and other fuels (natural gas, biogas, naphta). Normally, hydrogen produced on-site is in gaseous form at a pressure of less than 50 bar, so it has to be compressed further for refuelling. Centrally produced hydrogen can be delivered in gaseous form as CGH₂, or in liquid form as LH₂, with CGH₂ dominating.

In the case of gaseous hydrogen, the pressure stage at which the vehicles are served is important. At present, refuelling stations operate at the two pressure stages of 350 bar and 700 bar, and at the current stage of development the split is roughly equal (HyARC 2017). Around 20% of all refuelling stations currently offer both pressure stages, but the trend is towards the higher pressure stage, with the advantages of a larger volume of hydrogen stored and hence an improved vehicle range.

90% of refuelling operations for fuel cell electric vehicles are with gaseous hydrogen. Currently only a few refuelling stations offer both possibilities, or concentrate on liquid refuelling (HyARC 2017).

The supply options for hydrogen (delivery as CGH₂, or LH₂ in trailers or by pipeline; on-site production) can be combined with the dispensing options (gaseous at 350 or 700 bar; liquid and the size and design of the refuelling station (storage concepts, etc.).

Table 32 shows four typical hydrogen supply and distribution pathways. All pathways assume the purchase of compressed hydrogen at 700 bar; the dispenser is the same in all cases. Refuelling should take between three and five minutes for a full tank. The four supply pathways map at a time line the first two pathways are already relevant in the short- and medium-term and differ in terms of the type of hydrogen supply: in the first case hydrogen is delivered in gaseous form, in the second pathway it is produced on-site. The first refuelling station would currently be limited to a trailer delivery and hence to approximately 500 kg hydrogen per day. With on-site production there would be no delivery restrictions, although the electrolyser must reliably produce the required amounts of hydrogen. The investment costs are also higher. Onsite production can be scaled up if necessary. However, functional modules such as the storage tanks, compressor or dispenser need to be resized in some circumstances. Hydrogen pathways 3 and 4 are only relevant in the mid- to long-term or for a larger hydrogen requirement. Pathway 3 is based on a liquid delivery, which can bring larger amounts to the refuelling station and can manage with less space. Only in the longer term will hydrogen be produced centrally by electrolysis and transported to the refuelling station via pipelines. The space requirement can then be neglected, virtually any number of vehicles can be served. As in the previous case, the size and number of dispensers need to be adapted accordingly.

8.7 COSTS & FINANCING

As comprehensive an infrastructure as possible is an important factor for the acceptance and market success of a new technology — and that is also true of hydrogen and fuel cell vehicles. However, building that infrastructure requires high initial capital investment. The question is how high these investment costs will be and how a hydrogen refuelling station infrastructure can be built as efficiently as possible. There are a number of information problems associated with estimating refuelling station costs. Firstly, the costs of setting up a hydrogen refuelling station depend on the location solution, the size of the refuelling station and local conditions. For competition reasons, cost data is often confidential and is not published. Furthermore, the hydrogen stations that have been built to date have mostly been designed as one-off projects. Post building outlay therefore is not a reliable indicator for future construction costs in a more developed market. And lastly, there are currently only a few publications on hydrogen refuelling station costs.

In-depth studies on hydrogen refuelling station costs are only available from California so far (INRiL 2013; EVC 2014; CEC/CARB 2017). According to these studies, there is a big spread in investment costs for hydrogen refuelling stations, ranging from 1 million to 10 million USD. The costs for the most important refuelling station concepts with daily capacities of around 200 to 300 kg hydrogen are between 2 and around 3 million USD, with expenditure on fixed assets amounting to 1.5 to 2 million USD. For Germany, lower costs of around 1 million EUR per refuelling station are cited (Bonhoff 2016).

As a metric, capital costs based on daily dispensing capacity have emerged. In absolute terms, investment costs for smaller hydrogen refuelling stations are lower than for large ones. However, the capacity-specific capital costs range from almost 15,000 USD per kg per day for small stations to approximately 3,000 USD per kg and day for large stations supplied with liquid hydrogen. These low capital costs are only achievable with high capacity utilisation, however. Refuelling stations with on-site hydrogen electrolysis are much more expensive than centrally supplied stations, specifically, over 20,000 USD per kg and day, which is attributable to the high investment costs for the electrolyser.
GLOBAL HYDROGEN MOBILITY INITIATIVES

Germany (H2 Mobility/CEP)

The Clean Energy Partnership (CEP) industry consortium (www.cleanenergypartnership.de) for the development of an automotive hydrogen economy in Germany was established as early as 2002. Between 2012 and 2016 the CEP undertook the task of creating a basic hydrogen supply network, with 50 refuelling stations in Germany (CEP 2016).

The operating company H2 Mobility (www.h2-mobility.de) was established in 2014. H2 Mobility is a joint venture which is engaged in building and operating a network of hydrogen refuelling stations in Germany. H2 Mobility is also sourcing the hydrogen for its entire network, where possible from renewable energies. H2 Mobility’s plan is to set up the first 100 hydrogen stations by 2018/2019, unconditionally and irrespective of fuel cell electric vehicle numbers, preferred locations are the metropolitan areas and hydrogen corridors along the motorways. Depending on the registration figures for fuel cell vehicles, a comprehensive hydrogen infrastructure with 400 hydrogen refuelling stations in Germany should then be established by 2023.

As of the beginning of 2017 there were 35 to 40 CEP hydrogen refuelling stations operating in Germany. The CEP refuelling stations are being transferred to H2 Mobility. As a national hydrogen lighthouse project, the CEP will pursue tasks involved in developing hydrogen technology and standards.

EU/Europe (FCH JU, H2 Mobility, EU AFID directive)

In Europe there are a whole host of project-based, cross-border hydrogen/fuel cell initiatives – for example between European cities or for bus fleets. An important initiative is the Fuel Cells and Hydrogen Joint Undertaking (FCH JU), a partnership between the EU Commission, industry and research institutes. Its aim is to make the fuel cell and hydrogen pillars of the future European energy and transport system (www.fch.europa.eu). The second phase of the initiative (FCH JU 2) is scheduled to run up until 2020, with projects running until 2024.

Furthermore, the national hydrogen initiatives from Germany, Great Britain, Scandinavia and France have established a European hydrogen platform called Hydrogen Mobility Europe (www.h2me.eu). Hydrogen Mobility Europe consists of two project parts: H2M1 and H2M2. The goal is to develop a pan-European infrastructure of hydrogen refuelling stations and fuel cell electric vehicle fleets in a coordinated manner. Today, H2M involves more than 40 Partners from 9 countries, drawing together their expertise from across the transport, hydrogen and industries. In addition, Denmark, Norway and Sweden are represented in the Scandinavian Hydrogen Highway Partner- ship SHHP (www.sandinavianhydrogen.org).

Moreover, in 2014 the EU established minimum requirements for the infrastructure for alternative fuels, including hydrogen, through the AFID directive (2014/94/EU). This directive requires the EU member states to provide a reasonable number of hydrogen refuelling stations by 2025 in order to secure the movement of hydrogen-powered fuel cell electric vehicles (EP/Council 2014a).

USA/California (H2USA, CoCfP)

There are a number of hydrogen initiatives in the USA, including the nationwide public-private initiative H2USA (www.h2usa.org). The state of California is leading in the words of the hydrogen refuelling station infrastructure and fuel cell electric vehicle development. California is accelerating the phasing-in of so-called zero-emission vehicles within the vehicle fleet, just as battery electric vehicles fuel cell electric vehicles are regarded as ZEVs.

The California Fuel Cell Partnership CoCfP (www.caftp.com) was established in 1999 under the leadership of the California Air Resources Board and the California Energy Commission. The CoCfP has already set up a number of multi-annual programmes, most recently (2012) a roadmap for the five-year period until 2017. Accordingly, over 84 refuelling stations should be available by then, corresponding to a demand of around 53,000 vehicles (CoCfP 2012). More than 30 hydrogen stations were set up in 2016, and another 20 are under construction or going through approval procedures (CoCfP 2016).

Japan (HySUT)

The governmental organisation New Energy and Industrial Technology Development Organization (NEDO) is also driving forward the development and commercialisation of hydrogen technology in Japan. The relevant hydrogen technologies include domestic use (En-E-Fuel) and use in power plants and transport. The Association of Hydrogen Supply and Utilisation Technology HySUT (www.hysut.or.jp/en/) was founded in 2009 under the umbrella of the NEDO. Its original aim was to promote the technical preconditions for a future hydrogen infrastructure.

Following a reorganisation in 2016, HySUT is now engaged in the commercialisation of the hydrogen supply system and of hydrogen-powered fuel cell electric vehicles. Areas of interest also include issues surrounding technology/consumer acceptance and demonstration projects. The technology and market demonstration phase was followed in 2016 by early commercialisation. This is due to be completed in 2025, with a move to full commercialisa- tion from 2026. The number of hydrogen-powered vehicles has increased steadily. As of the beginning of 2017 there are already around 90 refuelling stations operating in Japan, and this number is scheduled to rise to 160 by 2020.

The transport sector currently (2014) consumes around 28% of the global final energy consumption and causes 23% of the energy-related greenhouse gas emissions (IEA 2016a). Around three-quarters of global transport emissions come from road transport. Road transport worldwide was responsible for around 5.7 gigatonnes of carbon dioxide emissions (CO2) in 2014. This corresponds to a share of 17.5% of the energy-related CO2 emissions worldwide.

Between 1990 and 2014, road traffic-related CO2 emissions grew by 71% worldwide, emissions from road traffic in the industrial nations (OECD) also increased over this period by 30% (IEA 2016a). Despite measures to avoid traffic or to shift it to public transport or more environmentally sustainable modes of transport, road traffic worldwide is still increasing. Therefore, reducing the energy, especially the fuel consumption, and the environmental impact of motor vehicles is all the more important. Overall the energy consumption and the environmental impact of motor vehicles are determined by, along with the vehicle mileage, their specific energy consumption. Fuel consumption is substantially predetermined by the choice of drive type. The drive also influences the greenhouse gas emissions and, together with the energy conversion process, the resulting air pollutant emissions.

ENERGY & ENVIRONMENTAL BALANCES, SCENARIOS FOR FCEVs

The specific energy consumption per km of a motor vehicle is determined by its weight and form, by environmental and driving conditions and by the efficiency of the drive type. The passenger car considered is an average passenger car in the respective region, i.e. a C segment passenger car for Europe and Japan and a mid-sized light-duty vehicle (LDV) for the USA. The efficiencies of different drive types vary significantly. In particular, electric drive types, both battery electric and fuel cell electric vehicles, have much higher efficiencies than internal combustion engines.

Thus, the Tank-to-Wheel (TTW) efficiencies of conventional petrol passenger cars are only about 20% and 30% for hybrid petrol passenger cars. Fuel cell electric vehicles at least achieve TTW efficiencies of up to 50%, while battery electric vehicles can reach around 70% (Kociyczy 2014).

Like the vehicle ownership cost calculation, the scenario assumptions regarding the European vehicle fleet development are based on the specific fuel consumption figures from (JEC 2013). These are recorded in the New European Driving Cycle NEDC. It is assumed that consumption figures of newly registered vehicles will disseminate into the passenger car fleets in the long term. It should be noted that JEC standard consumption figures for the 2020s and beyond assume significant improvements in efficiency. The standard specific fuel con- sumption figures were converted into real specific fuel consumption by using real world fuel consumption factors (ICCT 2014).

An estimate of technological progress and associated specific efficiency improvements and greenhouse gas emission reductions for passenger cars extending beyond the 2020s up to 2050 was provided in (AEA 2012). ICE passenger cars may achieve specific fuel savings of up to 50% by 2050, as compared with the reference technology in 2010. These specific efficiency improve- ments were applied to the JEC fuel con- sumption figures up to 2050. However, the efficiency improvements for the petrol drives from 2040 onwards is limited due to technological restrictions.

The Shell Hydrogen Study 56
The fuel consumption figures for Japan were assumed to be the same as for Europe. The specific energy consumption of US passenger cars was based on the values from (GREET 2015), which are somewhat higher than European consumption figures.

**9.2 GREENHOUSE GAS EMISSIONS**

In order to compare the carbon dioxide emissions of passenger cars, relevant greenhouse gases for transport fuels in the greenhouse gas intensity of crude oil are in a first step compiled for hydrogen, petrol, and electricity. For this purpose, the greenhouse gas emissions for the entire fuel and energy supply chains are taken into account. In a second step, distance-related greenhouse gas emissions (in g CO₂/100 km) for the vehicles are calculated and discussed.

**GREENHOUSE GAS FACTORS FOR TRANSPORT FUELS**

Regarding greenhouse gas emissions, a distinction must be drawn between Tank-to- Wheel emissions (TTW), which arise from burning a fuel in the engine, and Well-to- Tank emissions (WTT), which are caused upstream by the production and supply of the fuel. Well-to-Wheel emissions (WWW) are used to assess the entire supply chain for the fuel including its use, i.e. from the source of primary energy conversion into kinetic energy for propulsion.

Burning fossil energy sources produces carbon dioxide, which largely determines the greenhouse gas balance of motor vehicles with an internal combustion engine. Other greenhouse gases can also arise upstream in the supply chains of all fuel types or energy sources. The most important of these other greenhouse gases (methane, CH₄, and nitrous oxide, N₂O) are also taken into consideration in the overall greenhouse gas balances. Where reference is made to CO₂, the other greenhouse gases are also included in CO₂ equivalents. The terms “greenhouse gas (GHG) emissions” and “carbon dioxide (CO₂) emissions” are used synonymously below.

The specific greenhouse gas emission factors were compiled on the basis of the fuel production pathways and fuel-specific combustion factors from the last edition of the WtW studies by the European research platform of Joint Research Centre of the European Commission, Eucar and Concawe (JEC 2014) for Europe. The basic data from the JEC study was also taken into consideration by the European Commission in establishing typical and standard values for reducing greenhouse gas emissions for biofuels in the EU Renewable Energy Directive 28/2009/EC (EP/ Council 2009a) and the EU Fuel Quality Directive 30/2009/EC (EP/Council 2009b) as well as the associated directive 2015/62/EU (Council 2015) which lays down methods for calculating the greenhouse gas intensity of fuels and energy supplied other than biofuels and reporting by suppliers. The same greenhouse gas factors have been assumed to be valid for Japan.

For the USA the greenhouse gas factors are taken from “Greenhouse gas Regulations, Emissions, and Energy use in Transportation Model”, “GREET model” for short, published by the Argonne National laboratory of the Department of Energy (DOE) of the US federal government (GREET 2015). The GREET model is used in modified form to establish the fuel pathways of the low Carbon Fuel Standard (LCFS) in California (CCB 2017).

For the scenario calculations CO₂ emission factors were determined for three fuel types: petrol, as only petrol cars are considered as the internal combustion engine reference, electricity for battery electric vehicles (BEVs), and hydrogen for fuel cell electric vehicles (FCEVs).

Petrol

The WtT emission factors from the JEC study (JEC 2014) for petrol were modified in accordance with a recalculation of the greenhouse gas intensity of crude oil inputs into the EU (JCG 2014b) and thus correspond to the values in the above-mentioned EU directive laying down calculation methods for the EU Fuel Quality Directive (Council 2015). Moreover, the WtT emission factors for petrol are assumed to be constant over the period up to 2050. Since the specific factors for petrol are standardised, unchanged CO₂ emission factors for its combustion (g CO₂/MJ) are assumed.

For all regions under consideration, petrol containing 10% bioethanol is assumed for the medium to long term. For the EU (and Japan), the bioethanol blend meets the sustainability requirements of the EU Renewable Energy Directive 28/2009/EC (EP/Council 2009a) and of the EU Fuel Quality Directive 30/2009/EC (EP/Council 2009b).

For petrol in the USA the WtT emission factors for $10 from the GREET model (GREET 2013) apply.

**GREENHOUSE GAS FACTORS FOR VEHICLES**

Electricity

Depending on the type of primary energy source used and the conversion technologies for generating electricity, the carbon dioxide emissions in electricity generation vary widely. For electricity a clear change in the generation structure and hence also in its specific emission factor is anticipated because of a growing proportion of renewable electricity generation in the electricity generation mix by 2050.

The 450 scenario developed by the International Energy Agency (IEA 2016b) describes the preconditions that must be met by the energy sector overall and by the electricity sector in particular in order to achieve the 2°C climate action goal. The greenhouse gas emission factors for the European, Japanese and US American electricity mix are derived from the ambitious 450 scenario and are extrapolated to 2050. In particular, the IEA 450 scenario requires a major decarbonisation of the electricity sector through a strong expansion of renewable energies.

**Hydrogen**

There are also different supply pathways for hydrogen. Today, hydrogen is primarily obtained by steam reforming of natural gas. In the midterm, a growing proportion of biogas from municipal waste is assumed, up to 10% by 2030 and dropping down again to 0% in 2050. In the longer term, hydrogen generation by electrolysis on the basis of surplus renewable electricity is gaining ground, reaching 100% by 2050, to enable greenhouse gas emissions to fall by 80% as compared with 1990. The calculation of the greenhouse gas emission factors of the hydrogen mix over time is based on the emission factors from JEC (2014) for the individual supply pathways. For the USA the corresponding supply pathways from (GREET 2015) are used.

**34 SPECIFIC WELL-TO-WHEEL PASSENGER CAR GREENHOUSE GAS EMISSIONS “REAL WORLD” DRIVING CONDITIONS, EUROPE**

For the growing FCEV fleet is generated entirely from renewable sources (e.g. wind power) and only the electrical energy needed at the refuelling station to compress the hydrogen is taken from the electrolysis mix according to the IEA 450 scenario. As a consequence, the WWY greenhouse gas emissions of the FCEV are slightly lower than those of the BEV.

The introduction of electric drives, particularly with a fuel cell, into the vehicle fleet provides an important lever for reducing the greenhouse gas emissions of motorised private transport if vehicle electricity and hydrogen are also produced with a low greenhouse gas output.

**9.3 SCENARIOS FOR FCEVs**

In addition to the 450 scenario in its World Energy Outlook, the International Energy Agency in its Energy Technology Perspectives (ETP) has developed a second technology-oriented 2DS scenario, which likewise describes how the 2°C goal can be met (IEA 2015a). While “450” denotes 450 parts per million CO₂ (the maximum atmospheric CO₂ concentration for the 2°C scenario) and considers a projection to 2040, 2DS stands for 2 Degrees Scenario and extends as far as 2050. Both scenarios assume a rapidly accelerating technological improvement and set high requirements for reducing emissions in the conversion and consumption sectors of the energy system, and thus also in transport, by 2050.
In the 2DS scenario, the IEA expects hydrogen and fuel cell technology to contribute substantially to the energy and climate goals. In the transport sector, the fuel cell drive can contribute significantly to reducing the greenhouse gas emissions of motorised private transport. Depending on the way in which the hydrogen is produced, and especially if it is produced from renewable energy sources, in a WW consider the greenhouse gas emissions of a fuel cell electric passenger car can be reduced by more than 90% as compared with a petrol engine vehicle.

The IEA has published a “technology roadmap” for hydrogen and fuel cell electric vehicles (IEA 2013b), which is based on the 2DS scenario and, in a variant of that scenario, examines how an accelerated introduction of hydrogen technologies can contribute to achieving the 2°C goal (2DS high H2).

For the transport sector in the USA, Japan and the four major Western European markets of Germany, France, Great Britain and Italy (EU4), the 2DS high H2 scenario describes an increase in the number of FCEVs to well over 100 million vehicles by 2050. This assumes a rapid market expansion for fuel cell electric vehicles in the three automotive regions. According to this scenario, 1 million new FCEVs will have to be registered in both the USA and EU4 by 2030 in order to achieve the 2DS goals. In total, there would then be almost 10 million new FCEVs in the three market regions in 2050. As a comparison, approx. 74 million new passenger cars are registered each year worldwide at present (VDA 2016), and 2050 the annual number of newly registered passenger cars would have to be expected to be over 100 million cars.

Figures 35 and 36 show the development of the FCEV fleets in the three regions in question. The biggest absolute rise, to almost 60 million FCEVs in 2050, takes place in the USA. Around 35 million fuel cell vehicles are anticipated in the four European countries (EU4) and some 20 million in Japan in 2050. In total, around 111 million new fuel cell passenger cars will be registered in 2030 and around 113 million in 2050.

As a comparison, there are currently over 1 billion passenger cars worldwide (VDA 2016), and the number is expected to reach around 2 billion vehicles by 2050.

The energy demand of FCEVs can be calculated by multiplying annual mileage with specific energy consumption figures. The typical annual mileages differ substantially in the markets in question. For the USA a mileage of approximately 18,000 km/year is assumed, for Europe approximately 13,000 km/year and for the densely populated Japan 9,000 km/year. These average annual mileages are assumed for all vehicles considered, independent of their drive type. Moreover, annual mileages are assumed to remain constant until 2050. The calculated annual hydrogen demand for the number of vehicles according to the 2DS high H2, scenario is shown in figure 37. While the hydrogen demand in Japan develops moderately, it rises significantly for EU4 and especially for the USA. In total it rises to 1 million t in 2030, to a little over 5 million t in 2040 and to 10 million t in 2050. This corresponds to an energy equivalent of around 1,200 petajoules or to the energy content of 27 million t of petrol. If in addition the much higher efficiency of fuel cell vehicles in comparison to petrol drives is also taken into account, the use of fuel cell cars compared to petrol vehicles can lead to savings of up to 38 million t of petrol compared to hybridised petrol vehicles and up to 68 million t compared to a pure petrol drive.

If this hydrogen is to be obtained by electrolysis from renewable electricity, the requirements for hydrogen production are as follows: for the USA this would mean a wind and solar electricity requirement of over 330 TWh. For EU4 the figure would still be more than 100 TWh and for Japan more than 40 TWh. For the purposes of comparison, IEA (2016b) anticipates in the 450 scenario a reduced electricity production in 2040, compared with today’s figures, of 4,752 TWh for the USA, 3,314 TWh for the EU and 884 TWh for Japan.

With a growing proportion of hydrogen from renewable sources by 2050, the rise in fuel cell electric vehicles offers a significant greenhouse gas savings potential in the vehicle fleet. Assuming that the FCEVs will primarily replace cars with a petrol drive, this suggests a WW greenhouse gas savings potential of over 190 million t per year and a TWh greenhouse gas savings potential of over 180 million t per year in the three regions of interest in 2050 (figure 38).

This savings potential is broken down across the three regions as follows: in the USA WW savings of over 125 million t CO2 per year and TWh savings of up to 130 million t CO2 are possible. In EU 4 WW savings of up to 49 million t CO2 and TWh savings of up to 45 million t CO2 are possible, and finally in Japan WW savings of 18 million t CO2 and TWh savings of 14 million t CO2 are achievable. Taken over the entire period up to 2050, savings of over 1.5 gigatonnes WW and around 1.6 gigatonnes TWh are possible in the three regions, as compared with petrol alternatives.

FCEVs save 100% of TWh emissions. For that reason in the cumulative consideration up to 2050 this proportion is larger than the WW savings, in which, taken as a whole, higher WtW emissions from FCEVs compare with lower WtW emissions from petrol drives.

The emission reductions achieved in the 2DS high H2 scenario can be ranked by reference to the total traffic-related greenhouse gas emissions of the New Policies Scenario (NPS) developed by the International Energy Agency (IEA 2016b) for 2014. This scenario is the “baseline scenario” in IEA (2016b) and describes the development of the energy sector based on the confirmed climate action commitments by governments with regard to energy and greenhouse gas savings, and thus reflects the current situation. The NPS shows annual traffic-related emissions of approx. 1.7 million t CO2 for the USA, around 860 million t CO2 for the EU and around 210 million t CO2 for Japan. Only TWh emissions are considered in this scenario.
HYDROGEN - ENERGY OF THE FUTURE

Over the years Shell has published a number of scenario studies on key energy issues. These have included studies on important energy consumption sectors such as passenger cars and commercial vehicles (lorries and buses), and the supply of energy and heat to private households, as well as studies on the state of and prospects for individual energy sources and fuels, including biofuels, natural gas and liquefied petroleum gas.

Hydrogen is an element that receives significant attention. As an energy source, hydrogen has long been considered a possible basis for a sustainable energy future. But it cannot be viewed in isolation, since it is both in competition with and interdependent on other energies and the technologies that use them. The question is whether hydrogen can be an important energy carrier of the future.

Shell has been involved in hydrogen production as well as in hydrogen research, development and application for decades, with a dedicated business unit, Shell Hydrogen. Now, in cooperation with the German research institute and think-tank Wuppertal Institute, Shell has conducted a study on hydrogen as a future energy carrier.

The Shell Hydrogen Study looks at the current state of hydrogen supply pathways and application technologies and explores the potential and prospects for hydrogen as an energy source. The study also examines non-energy uses and non-autonomous applications, but its focus, as indicated by its subtitle Sustainable Mobility Through Fuel Cells and H2, on the use of hydrogen in road transport and specifically in fuel cell electric vehicles.

THE ELEMENT HYDROGEN

Hydrogen was the first element created after the Big Bang. It is the commonest substance in the universe and the richest energy source for stars like the sun. Hydrogen [H] is the first element in the periodic table of chemistry and is also the smallest, lightest atom. Pure hydrogen occurs on Earth only in molecular form (H2). Hydrogen on Earth is usually found in compounds, most notably as water molecules (H2O).

First discovered in the 18th century, hydrogen was originally known as “inflammable air.” By the 19th century hydrogen was featuring in contemporary visions of the future, especially in relation to the energy industry and locomotion. In the 1960s and 1970s space travel and the increasing scarcity of resources further intensified the aura of excitement surrounding hydrogen. Since the 1990s the interest in hydrogen has been boosted by the growing urgency to find sustainable energy sources. More recently, the focus has been on hydrogen’s role in an increasingly electricity-based energy economy.

Owing to its special physical properties, hydrogen is an almost permanent gas, since it only liquefies at very low temperatures (below -253°C). It has a low density, so it is usually stored under pressure. Liquefaction increases its density by a factor of 800. The most characteristic property of hydrogen is its flammability. It also has by far the highest gravimetric energy density of all energy sources in use today. Due to its chemical properties, hydrogen has to be handled with care.

SUPPLY PATHWAYS

Since hydrogen usually exists on Earth as part of a compound, it has to be synthesised in specific processes in order to be used as a material or energy source. This can be achieved by different technical methods, and various primary energy sources – both fossil and renewable fuels, in solid, liquid or gaseous form – can be used in these technical production processes.

The most important primary energy source for hydrogen production currently is natural gas, at 70%, followed by oil, coal and electricity (as a secondary energy resource). Steam reforming from natural gas is the most commonly used method for hydrogen production. Other production methods include partial oxidation, autothermal reforming and gasification, which generally use fossil primary energy sources. Some unused residual hydrogen is available for energy use as a byproduct of industrial production processes.

To date, only small amounts of hydrogen have been generated from renewable energies, although that amount is set to increase in future. Electrolysis currently accounts for around 5% of global hydrogen production, but most of it is still based on conventional electricity sources. Electrolysis from surplus renewable power is seen as offering huge potential for the future. Alkaline electrolysis has been used in the industry for more than a century. Alternative electrolysis methods offering improved performance parameters (regarding conversion efficiency, flexibility and costs) are currently in development.

Hydrogen production from biomass, while technically feasible, is still insignificant on a global scale, and while thermochemical methods such as biomass gasification and biogas reforming are already in use, biochemical processes are still in their infancy. The availability of biomass has to be checked against sustainability requirements, since it is a limited resource.

STORAGE & TRANSPORTATION

The specific physical and chemical properties of hydrogen lead to higher logistics costs (storage and transportation) than for other energy carriers. Hydrogen has a very low volumetric energy density, which means that it has to be compressed for storage and transportation purposes.

Commercially most important is the hydrogen storage as compressed gas. For end users, high-pressure storage tanks of varying design (350, 700 bar) are available. A higher density for storage can be achieved by liquefaction, although this involves cooling the hydrogen to -253°C.

APPLICATIONS

Hydrogen is a highly versatile basic chemical with two main areas of use: material applications and energy applications. The most important material applications are hydrogen and industry are ammonia synthesis, primarily used for the production of nitrogenous fertilisers, and methanol synthesis. Also, hydrogen is a by-product of crude oil refining in refineries, in particular catalytic reforming of naphthas, on the other hand it is used for the processing and refining of oil products in refineries – in processes such as hydrocracking and hydrocracking, for example. Energy applications involve converting the energy contained in hydrogen into heat, power or electricity. However, hydrogen is now rarely used as an energy source in heat engines.

For energy applications, fuel cells have become the main focus of hydrogen usage. Fuel cells offer much higher electrical efficiency and overall efficiency than heat engines. The fuel cell principle was discovered back in the 19th century: with a continuous supply of fuel, chemical energy
and oxygen are recombined into H2O – distinguished in terms of the electrolytes many different cell types now available are is converted directly into electrical energy.

Stationary fuel cells are an important driver of global market development for fuel cell systems, in terms of both numbers and installed capacity.

Fuel cells can be used as an alternative to generators and rechargeable batteries as a backup power supply, in the form of either emergency generator sets or uninterruptible power supplies (UPS). Since fuel cells generate electricity and heat, their use in combined heat and power (CHP) units for electricity and heating supply in the power plant sector and the building sector is increasing.

Micro-CHP fuel cell systems, due to their high overall efficiency, are a promising new option for energy-efficient domestic energy supply. Fuel cells for domestic energy supply generally run on natural gas (with additional external or internal reforming). The first commercial micro-CHP units based on PEMFC and SOFC fuel cells are now available for the construction resp. building sector. Major demonstration projects and market launch programmes for domestic fuel cell systems have already been introduced in Germany, Europe and Japan, under the names “Callux”1; 2 “sill field”3 and “Ena-Farm”4. By the end of 2016, almost 200 micro-CHP units had been installed in Japan under the Ena-Farm programme, by 2030 the Japanese government wants to have installed 5.3 million CHP units.

The economic efficiency of fuel cell micro-CHP or mini-CHP units in the building sector is dependent on the respective electricity and natural gas retail prices. The wider takeup of CHP technology in buildings will require (in the short term) further temporary funding to develop the market.

MOBILITY APPLICATIONS

Hydrogen can be used as an energy source for mobility applications. Initially, it was also tested in internal combustion engines, but in the transport sector hydrogen is now used almost exclusively in fuel cells. Space travel provided the historical and technical impetus for the development of hydrogen and fuel cell technology. In principle, hydrogen fuel cell systems are suitable for virtually all means of transport, but their technological maturity varies according to the means of transport and the way in which it is used. The technological maturity of a product can be determined in terms of Technology Readiness Levels (TRL), a system developed by the US space authority NASA. The TRL scale goes from levels 1 to 9. Sufficient technological maturity, which means at least proven functionality in the field of use (= TRL 8), is a crucial prerequisite for a market launch in the respective mobility application areas.

Industrial trucks such as forklifts or tractor units for material handling are technically already at least TRL 6成熟 and can already be driven by internal combustion engines. Buses have undergone more intensive fossil testing than any other means of transport, thanks to public funding projects.

There is still a lot of development work to be done with regard to trains, ships and aircraft; light rail vehicles and commercial vehicles (including lorries) may benefit from proven bus or passenger car technology. There are no plans as yet for commercial aircraft or merchant ships, but they can use fuel cells as an efficient energy source for auxiliary power units (APUs).

ENERGY AND ENVIRONMENT: SCENARIOS FOR FUEL CELL ELECTRIC VEHICLES

Transport is an important energy consumption and emission sector. Worldwide, road traffic was responsible for around 5.7 gigatons of CO₂ emissions in 2014, and CO₂ emissions from road vehicles rose by 71% between 1990 and 2014. Given that road traffic worldwide is still increasing, despite measures to avoid traffic or to shift it into public transport or more environmentally sustainable modes of transport, reducing the energy consumption and negative environmental impacts of motorised vehicles is the most important.

Hydrogen-powered fuel cell electric vehicles (FCEVs) are much more efficient than passenger cars propelled by an internal combustion engine. So FCEVs can make an important contribution to the diversification of energy supply and to energy savings in motorised road transport. If hydrogen is generated from renewable energy sources, its specific greenhouse gas emissions over the entire supply chain are very low. Coupled with the more efficient drivetrain, this results in significantly lower distance-related greenhouse gas emissions...
as compared with internal combustion engine vehicles running on fossil fuels. Depending on the hydrogen supply pathway, FCEVs produce (slightly) higher/lower, but essentially similar, specific greenhouse gas emissions as compared with battery electric vehicles.

An ambitious “2DS high H2” scenario developed by the International Energy Agency in line with the climate action goal of limiting the global temperature rise to 2°C, assumes that the number of fuel cell electric vehicles in three key markets (USA, selected European markets and Japan) will increase to some 113 million units by 2050. This is based on a projected increase in annual FCEV registrations in the EU and USA to 1 million by 2030, rising to a total of 10 million new registrations per year in the three regions in question by 2050.

The further development of mobile and stationary fuel cells as the most important energy technologies for hydrogen use must be supported, in terms of manufacturing costs and efficiency as well as long-term stability, through technologically diverse R&D funding.

Hydrogen must be safe, easy and efficient to handle. Therefore there is a need for uniform, international, hydrogen-specific technical standards for plants and equipment and for hydrogen as a product.

The development of alternative technologies in areas with a very limited portfolio of mature, sustainable technologies (e.g. lorries, rail, ships, aircraft) requires further R&D funding.

Hydrogen is not (yet) a familiar product among end users. Rather, for the vast majority of consumers, hydrogen and the technologies that use it are still new. Novel energy technologies require openness, a willingness to learn and familiarisation on the part of future users. Therefore, education and the dissemination of relevant technological information are vital if such technologies are to gain acceptance among users and in society as a whole. This requires appropriate communication strategies and formats for building experience and commitment.

To speed up the establishment of a global hydrogen economy, synergies need to be created – through cooperation between cities, regions and states and with relevant economic operators. Linking up the production and consumption sectors is also important, as is a comprehensive coordination of innovative technologies like battery systems and fuel cells.

Considering the entire period between now and 2050, over 1.5 gigatons of greenhouse gas emissions could be saved, WttoWheel, as compared to the replaced petrol vehicles.
Hydrogen is an element that receives significant attention: As an energy carrier, hydrogen is considered to be the basis for a sustainable energy future. But hydrogen is not alone, since it competes with other energies and their application technologies. The question arises as to what extent hydrogen can or will play a leading role in the global energy system of the future. Shell has already been active for decades in hydrogen research and development. In cooperation with the Wuppertal Institute, Shell has now conducted an energy carrier study, which addresses the current status as well as the long-term prospects of the use of hydrogen, in particular for energy and transport purposes.

The Shell Hydrogen Study discusses firstly the (natural) occurrence, properties, and historical perspectives of the element hydrogen. It then examines current as well as future technologies/processes and source materials for the production of hydrogen, and it compares the energy requirements, greenhouse gas emissions and supply costs of the different production pathways. Furthermore, hydrogen logistics is investigated. That includes, on the one hand, current and future storage methods, and on the other, the various transport options and their respective benefits, including questions of transport economy.

This is followed by a description of the different potential options for the use of hydrogen. A distinction is made between the use in materials or for energy purposes/as an energy carrier. The analysis of hydrogen use for energy purposes focuses on the fuel cell – and not on the use in heat engines resp. combustion engines. On the user side, stationary energy applications for back-up electricity production as well as domestic energy supply – including their economics – are looked into.

The main focus of the study is on mobile hydrogen applications. For this purpose, the technological status and prospects of mobile applications – from aerospace, via material handling, through to the passenger car – are discussed. This is followed by an analysis of the economics of hydrogen-powered fuel-cell cars based on a simplified car cost comparison. Subsequently, the construction of a hydrogen retail station infrastructure for road transport is discussed.

Finally, the possible effects of fuel-cell cars on fuel consumption and greenhouse gas emissions in selected regions up to 2050 are discussed. This analysis is based on the ambitious 2DS hydrogen scenario from the International Energy Agency.