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Hydrogen – the Key to the Overall Energy Turnaround

Production and Application Examples in North Rhine-Westphalia

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Fuel Cell
and Hydrogen
Network NRW

Content

Foreword

Johannes Remmel
Minister for Climate Protection, Environment, Agriculture, Conservation and Consumer Affairs of the Federal State of North Rhine-Westphalia

North Rhine-Westphalia is Germany's most important energy state, accounting for around one third of the country's electricity output. Due to our predominant use of fossil energy, however, we are also the source of more than one third of the nation's emissions of climate-relevant gases. We therefore bear a special responsibility. The state government aims to make North Rhine-Westphalia a leader in climate-protection, and therefore resolved in June 2011 to reduce greenhouse-gas emissions by not less than 25 per cent by 2020, and by not less than 80 per cent by 2050, taking 1990 as the base year in both cases. These targets have been adopted as mandatory in our Climate Protection Act, and are to be achieved primarily by means of energy-savings, greater energy-efficiency and the expanded use of combined heat and power (CHP) generation and of renewable energy sources. Specific strategies and provisions which will permit the attainment of these state-wide climate-protection objectives are set down in the Climate Protection Plan.

The action taken in Germany as whole, and here in North Rhine-Westphalia specifically, cannot, of course, prevent climate change, but the entire world is nonetheless watching, spellbound, as the German "Energiewende" (energy turnaround) progresses. Success here will have great publicity effects, stimulate imitation, and boost even further global demand for our capabilities and technologies in this field. The broad and intensive discussion initiated here, and the participation of the general public, companies, associations, etc., which is unique throughout Germany, along with research into and testing of new technologies, assist us in pursuing our careful path: we intend to remain an industrial state and, furthermore, an industrial state with long-term prospects. Simply exporting emissions – and jobs – will help no one. The expansion of the use of renewable energy sources must be accelerated, however, because – given our current, predominantly coal-based, power generation industry – our targets can be met only in this way. This expansion will necessitate transmission grids and storage systems, broad access to variable prices, load management, and flexibly operable residual-load power plants based on low-emission fuels.

The subject of "energy storage" brings us to hydrogen. Batteries and pumped storage facilities have response times measured in minutes and even hours, whereas hydrogen, thanks to its high energy density and availability, is outstandingly suitable for medium- to long-term storage of large quantities of energy. The regulatability of electrolysers has increased significantly in recent years. Hydrogen can be "converted back" to new electricity (re-electrification), fed into the natural gas grid, or methanised. The greatest potential for reduction of emissions can, however, be found in the use of hydrogen for road transport, where fuel cells permit very significant gains in efficiency compared to conventional propulsion systems, combined with totally climate-friendly and simultaneously reduced-noise mobility. The large ranges and short fuelling times attainable will assure the widespread use of such vehicles. We are currently working on eliminating obstacles to achieving market maturity, among other things by means of initial projects for the supply of entire vehicle fleets. Hydrogen's potential contribution to reducing emissions in NRW is also being studied in greater detail.

In addition, fuel cells possess enormous potential for decentralised combined heat and power generation. Corresponding systems are currently being prepared for their market launch by two NRW-based manufacturers.

Fuel cell, electrolysis and hydrogen technologies also have the potential to contribute to "Climate Protection, Made in NRW" and, simultaneously, to become "export hits made in NRW". This entire technology, from individual components up to and including complete systems, is being developed and will be produced here in North Rhine-Westphalia. The new version of the "Hydrogen HyWay" lead project concentrates and intensifies the associated activities, which are coordinated within the state by EnergyAgency.NRW's Fuel Cell and Hydrogen Network NRW. This brochure provides you with important information on the development of these energy-turnaround technologies and their uses.

Introduction

Dr. Thomas Kattenstein
Head of the Fuel Cell and Hydrogen
Network NRW

New energy technologies which form the basis for advances in climate protection and efficiency are virtually always obliged to compete with the established state of the art. In many cases, they also require greater investments, a greater initial installation and maintenance input plus, in some instances, the setting-up of entirely new infrastructures. When, on an overall view, the mid- to long-term benefits outweigh the disadvantages, it becomes a social duty to smooth the road to market for such technologies by means of appropriate research, interchange of information and advisory services, however.

The Fuel Cell and Hydrogen Network NRW promotes precisely such an interchange. It was founded as part of EnergyAgency.NRW in 2000, with a total, at the time, of fifty members. The Network brings experienced and new players in the field of fuel cell and hydrogen technology together in order to jointly accelerate their development and market launches. Its aims are to provide support for emission reduction and climate protection during the energy turnaround, and to establish a corresponding sector of industry. The intensification of knowledge transfer between research and industry creates new spheres of activity for companies and institutions, and thus strengthens NRW production and research locations working in the field of fuel cell technology. The increasing involvement of users is the final stage prior to market launch. The now more than 440 members are based mainly in NRW, but with an increasing proportion from the Federal Republic of Germany as a whole, and from other countries.

The focus of current activities is on the investigation of a potential contribution by hydrogen as an energy storage medium to the expansion of the use of renewable energy sources in our state: hydrogen production using electrolysis processes, decentralised and central storage of this hydrogen, and downstream options for its use. The choices available include re-electrification (in hybrid power plants and fuel cells, for example), use as a feedstock in the chemical industry, the possibility of direct feed-in to the natural gas grid, and conversion of the hydrogen to methane. Of particular interest, however, always assuming the setting-up of an adequate infrastructure, is the use of hydrogen, in combination with fuel-cell-based vehicles, as an innovative fuel for transport purposes. Such applications could make a particularly significant contribution to the protection of the climate and the environment.

The fuel cell is a highly efficient energy converter, and is most certainly also capable of demonstrating its benefits in stationary applications, however. A fuel-cell-based micro CHP plant unit, for example, achieves ultra-high electrical efficiencies (of up to 60 per cent) and will thus boost the trend of buildings having ever decreasing heat needs.

An important aim in all these fields is that of enlarging the production quantities of market-ready systems by means of systematic publicity and sales activities, and thus reducing unit costs. Research, development and demonstration projects must be pursued in parallel, in order to improve the technology, enhance reliability and service-lives, and thus achieve further cost reductions. Our network will continue in the future to provide comprehensive support for its members via its diverse range of activities and services.

This brochure examines current developments in hydrogen and fuel cell technology in their various applications, via the overall process of innovation, from research up to market launch. The emphasis is, of course, on developments and examples in NRW which are, however, necessarily augmented with national and international aspects. Finally, we wish here to thank the authors for their contributions, and to wish you, our readers, an interesting and profitable read.

1 Hydrogen in the changing energy mix

Changes in our choice of energy sources and in our energy conversion methods are inevitable, in view of the global energy supply, environmental and climate-change situation. Advanced solutions are needed: fuel cells and new energy sources, such as hydrogen, will increasingly contribute to the safe, efficient and clean conversion of energy and to its cost-effective use. This is true, in particular, of hydrogen's new role in the restructuring of energy supplies as part of the overall energy turnaround.

Germany's politically decreed energy turnaround ("Energiewende") aims at achieving energy supplies with low greenhouse-gas emissions and a high percentage of renewable energy sources. This objective constitutes a significant technical and social challenge: the share of eco-power used is to increase to 35 per cent by as early as 2020, and greenhouse-gas emissions (GHG) in Germany are to be cut by 80 per cent (compared to 1990) by 2050. It will be necessary, as a basic precondition, not only to change the primary-energy structure (increasing the percentage of renewable energy sources) and the use of final energy (building optimisation, efficient domestic and industrial use of energy, plus increased electromobility), but also to reshape our infrastructures, including power and gas transmissions grids. An intensive social debate has started concerning the necessary time schedule, costs, public acceptance and political targets – including the integrated European energy system also necessary for the future.

Hydrogen today – a resource for the chemical industry

Hydrogen is nowadays an important feedstock for the chemical and petrochemical industries, and is used primarily for the production of ammonia (and its derivatives, fertilisers and plastics), and for the processing of oil to produce fuels and high-grade chemical products. Hydrogen is also needed for metallurgical reduction processes, as a coolant in electrical generators, as a shielding gas in electronic engineering, for welding and flame-cutting in mechanical engineering, and for fat saturation ("hardening") in the foodstuffs industry.

The use of hydrogen for "non-energy" and only "indirect energy" applications has definitively influenced the development of hydrogen technology and the safe handling of this gas over the past hundred years (Figure 1.1). Current global demand for hydrogen is around 540 billion cubic metres per annum (and some 20 billion cubic metres per annum in Germany alone). Demand for industrial hydrogen can be expected to continue rising. Around the world, hydrogen, a basic chemical industry requisite, is nowadays produced 96 per cent from fossil energy sources (primarily natural gas) and 4 per cent by means of electrolysis. Refineries and the coal-and-steel industries also produce significant quantities of hydrogen, which is, however, used at the production site. Only a small portion of global hydrogen production is traded in gaseous or liquified form as so-called "merchant hydrogen" and delivered to users by road or pipeline.

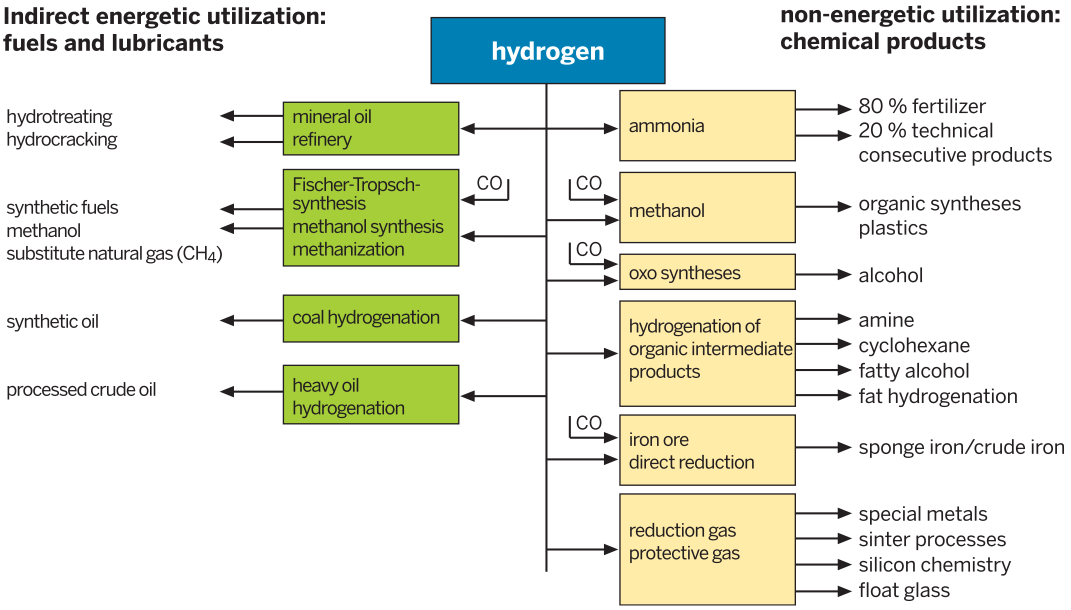

Figure 1.1: Hydrogen in the chemical industry (source: DLR)

Hydrogen – a key factor in the energy turnaround

Hydrogen has been present in our technology as an energy source since the times when “water gas” – the historical name for a mixture of gases containing around 50 per cent hydrogen by volume – was first generated from solid fuels. Hydrogen was also used in a mixture of gases for lighting and heating purposes in “town gas”, originating, for example, from coke-oven gas. The introduction of natural gas ended the era of gas mixtures on the energy market.

The production of hydrogen from wind and hydropower, and also from solar energy, is already technically possible, and will gain increasing importance in the long term as a key element in a globally sustainable energy industry (Figure 1.2). The fact that wind power, for example, is yielded only intermittently and can thus be directly used, depending on demand, only in individual cases, means that there is a need for a storable, transportable and environmentally friendly form of energy: hydrogen meets all these requirements for a chemical energy source.

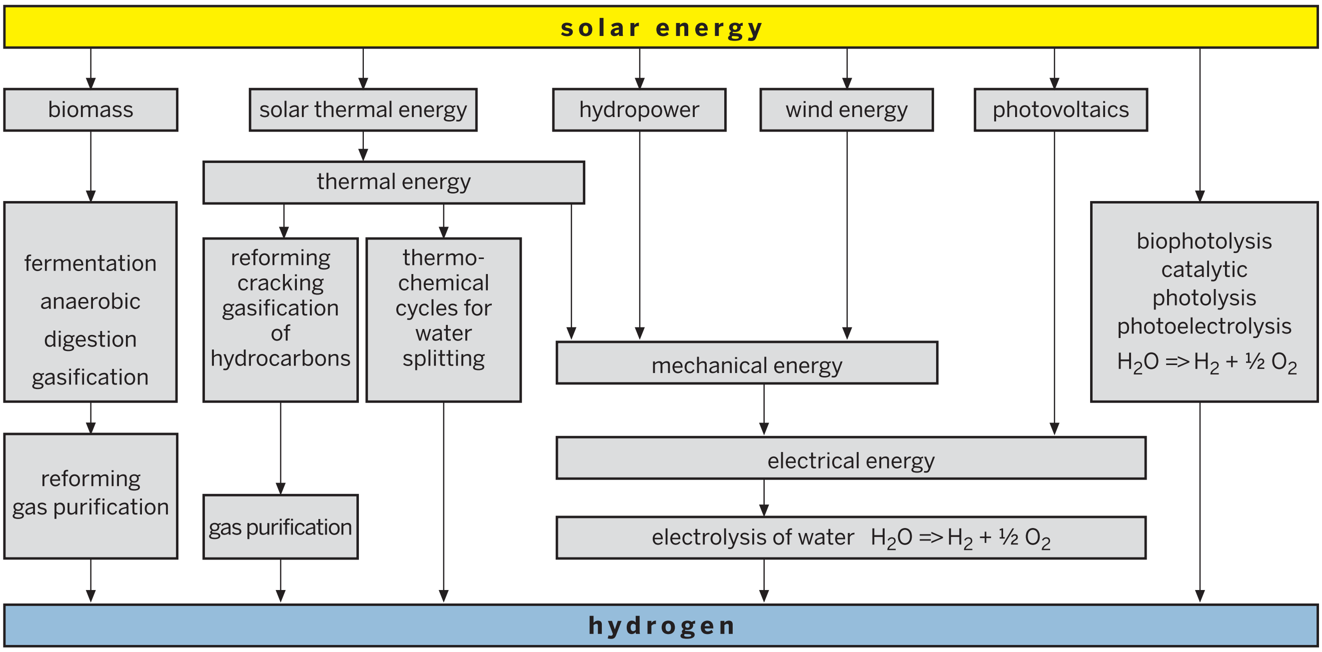

Figure 1.2: Energy-conversion operations in non-fossil production of hydrogen (source: after DLR)

Hydrogen is set to play an important role in the reorientated energy industry, as part of the politically adopted expansion of renewable energy sources during the energy turnaround, and in the associated implications for transmission grids and for the storage of energy. Hydrogen is a form of energy which makes it possible to store large quantities of surplus power – either in centralised form (in salt caverns) or in decentralised form (at filling stations).

Intermittent supply of power generated on the basis of renewable energy sources can then be partially balanced out via the regeneration of electricity from the hydrogen in fuel cells or gas-turbines. In this way, the generation and consumption of electrical energy can, to a limited extent, be divorced from one another. The potential for the direct use of electricity and hydrogen in mobility, using battery- and fuel cell driven electric vehicles, also provides optimum solutions for efficient, low greenhouse-gas transportation.

The extent to which hydrogen generated as a base load can be fed directly into the natural gas grid or can be converted, together with carbon dioxide, to methane, to permit the temporary continued use of existing natural gas infrastructures, remains to be ascertained for the transitional period of the next ten or twenty years. In any evaluation of the overall energy chain, such a conversion process leads to a significant loss of efficiency compared to the direct use of electricity and hydrogen (Figure 1.3).

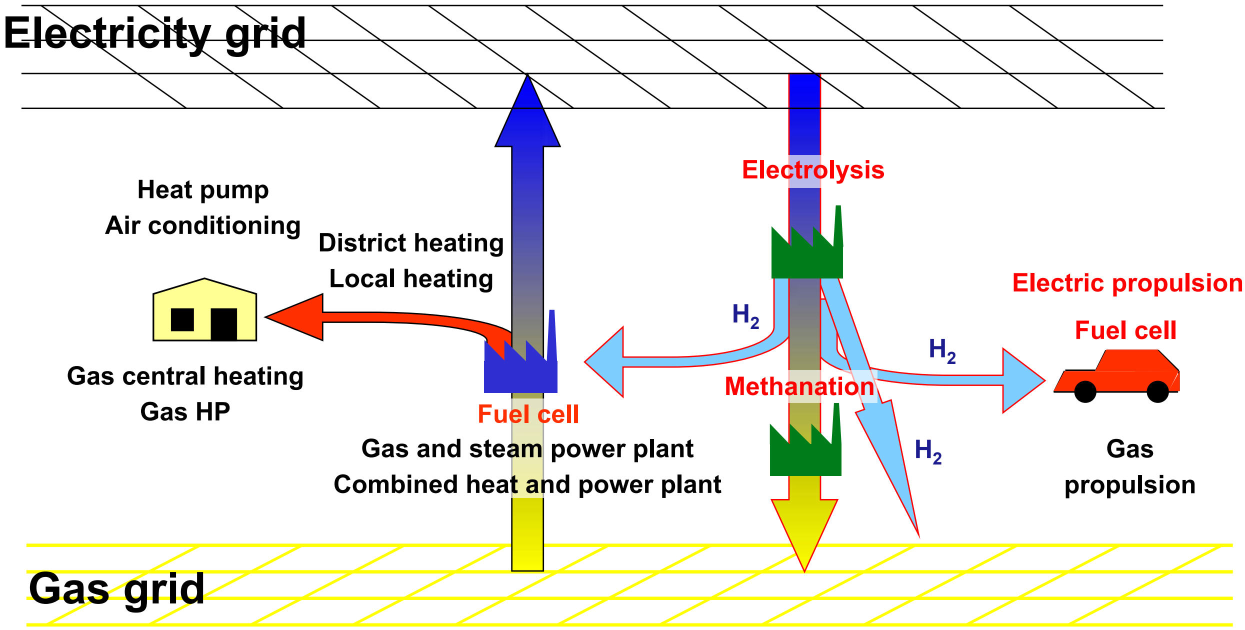

Figure 1.3: Regeneratively based hydrogen in the integrated energy system (source: after DLR)

Hydrogen – a clean fuel for transport

Both forms of energy – hydrogen and electricity – are currently available primarily only from fossil energy sources and have, up to now, scarcely been used for transport purposes, where fossil-origin gasoline and diesel continue to dominate. The development of the fuel cell, an electrochemical energy converter, demonstrates that the use of hydrogen and fuel cells produces significantly improved energy-efficiency and achieves extremely low greenhouse-gas (GHG) emissions in transport applications as soon as hydrogen is produced in a GHG-neutral way. The same also applies, analogously, to battery-powered propulsion systems for road traffic.

It is possible to show, taking the example of electromobility, that the energy evaluation for wind-power-based hydrogen production (including its use in fuel cell vehicles) may vary extremely compared to methane production (including its use in gasoline-engined vehicles as compressed natural gas [CNG]). It must be emphasised that the primary-energy requirement (well-to-wheel [WTW]), i.e., regenerative wind power, for the energy chain incorporating hydrogen/fuel cell propulsion is only 35 per cent of the primary-energy requirement for the methane/gasoline/CNG propulsion variant of the energy chain (H_2 via wind power and CO_2 from the air (source: after Höhlein/Kattenstein/Töpler (2013)).

According to the political concepts in Germany, battery- and fuel-cell-powered vehicles could account for a market share of around one million units by 2020. Despite significant advances in battery technology, a maximum range of around 150 kilometres for battery-powered cars continues to be assumed for the future, too: higher on-board battery capacities inevitably mean significantly higher vehicle weights. Charging times are also becoming longer and longer, with the result that quick “tanking up” is not possible. A hydrogen tank, conversely, can be filled in only a few minutes, while the achievable range varies between 400 and 500 kilometres even now. Both vehicle concepts will therefore have a place in future mobility: the “battery car” more in urban and suburban travel, with the fuel cell car also capable of longer journeys.

The special position of Federal State of North Rhine-Westphalia is notable for a density of commercial hydrogen production facilities unique throughout Europe, a significant yield in quantity terms of hydrogen as a chemical industry byproduct, and the existence of infrastructural elements (pipelines) which can serve as the nucleus for a graduated expansion of filling station networks.

The power-to-gas strategy

Demand-orientated integration of fluctuating renewable energy supplies into a cost-efficient balance between production and consumption constitutes a significant challenge for the future energy market. The conversion of renewable electricity into a storable gas and the expansion of energy-storage facilities and networks, are vital preconditions for this. Considerably more flexibility will be demanded from the energy system in future.

Figure 1.4 shows the power-to-gas concept as a link between the electricity and gas infrastructure and illustrates the following potential uses for hydrogen:

- Direct feed into the natural gas grid
- Reaction with carbon dioxide to form methane, followed by feed into the natural gas grid
- Direct use for mobility (fuel cell vehicles), industry (e.g. chemicals) and energy (re-electrification in a fuel cell CHP plant unit)

Thanks to the conversion of electricity from renewable energy sources (RES) to gas, the power-to-gas concept permits predictable availability of power generation according to wind availability and hours of sunshine. In the past, only low storage capacities for electricity were needed in order to provide supplies cost-efficiently and in accordance with demand using existing conventional power-generation plants. The rising amount of fluctuating feed-in of electricity in the next few years will occur mainly in the north or north-east of Germany. It will therefore be necessary to transmit electricity across long distances. Further expansion of RES will generate macroeconomic benefits only provided these energy sources can be integrated into existing energy systems and infrastructures. Existing underground – and thus, for the landscape, “invisible” – gas-pipeline systems can, initially, be used for conveyance of added hydrogen or methane. The existing, or an proprietary, hydrogen infrastructure will then later be used in NRW more intensively, directly or via underground storage caverns, for hydrogen generated by means of electrolysis. Existing and new gas storage facilities will also permit longer-term storage of the energy from different renewable sources.

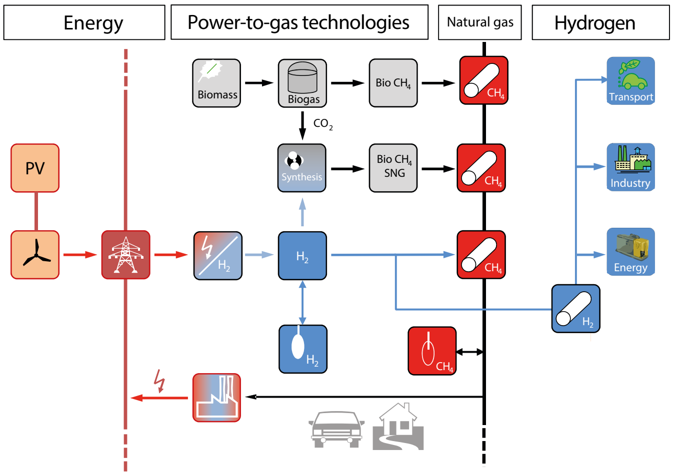

Figure 1.4: Energy storage and development of the future hydrogen market as a result of power-to-gas technology (source: Marius Adelt)

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Power-to-gas

Power-to-gas is a systems concept for the conversion of surplus electricity generated from renewable sources into hydrogen via electrolysis. The hydrogen can then be used to generate new electricity, or marketed to the transport sector for use in fuel cell vehicles. Storage and transmission infrastructures will be necessary. There is also the possibility of feed-in into the natural gas grid, either directly, or following methanisation of hydrogen using non-fossil carbon dioxide, and thus of using natural gas infrastructures for transmission, storage and utilisation. The convergence of the electricity and gas infrastructures generates significant synergy effects and assures improved utilisation of renewable electricity generating capacity, and also large hydrogen transmission and storage capacities, with the simultaneous setting-up of separate infrastructures for the use of hydrogen in vehicles and combined heat and power (CHP) facilities..

Further information on the “Potentials for feed-in of hydrogen into the natural gas grid – a seasonal observation” can be obtained from www.gwi-essen.de or in the German brochure “Wasserstoff – Schlüssel zur Energiewende” (2013, page 12) (www.energieagentur.nrw.de).

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Estimation of potential for the use of wind power in mobility via fuel cell vehicles

Due to the fluctuating yield of renewable energy, any significantly greater integration will necessitate new energy-storage solutions. In the current absence of the direct storage of electrical energy to the necessary extent, one option would be the use of surplus electricity for the generation of hydrogen via the electrolysis of water.

The following alternatives for utilisation of the hydrogen generated in this way are currently under discussion in the context of the energy turnaround:

- Re-electrification to balance out fluctuating feed-in from renewable energy sources
- Use as a fuel for vehicles with the highly efficient fuel cell propulsion system (FCV)
- Direct feed-in of hydrogen to the existing natural gas grid
- Methanation, for subsequent feed-in into the existing natural gas grid

One benefit of the second option is that the emission advantages of renewable-source generation of electricity would be extended to the transport sector. It would involve the replacement of energy sources with higher specific GHG emissions when compared, on the one hand, with the use of natural gas. In addition, an energy-efficiency better by a factor of two can be achieved via the use of fuel cell technology in vehicle propulsion systems.

Energy-supply concept

An energy-supply concept for definitive inclusion of regenerative production of electricity can be formulated on the basis of the above deliberations:

- Generation of electricity is based solely on renewable energy sources, with natural gas to cover residual demand
- Surplus electricity is used for the electrolytic production of hydrogen. Natural-gas-fired power plants are used only to balance fluctuating feed-in rates
- 50 per cent of the natural gas used in 2010 in the field of domestic heating is saved. This can be used for generation of electricity where necessary
- The hydrogen generated is distributed to the filling stations via a hydrogen pipeline system, and is used in fuel cell cars. Hydrogen is stored in salt caverns

Time-dependent plots of vertical grid load and of feed-in from renewable energy sources for Germany are used as the calculation basis. Installed capacities are 169 GW of on-shore wind power, 70 GW of offshore wind power and 25 GW of photovoltaics installations. An efficiency of 70 per cent referred to lower heating value is assumed for electrolysers. 1000 hours of operation at full load are assumed as the minimum utilisation rate of the last electrolyser added, to provide a capping threshold. A deduction of 15 per cent of present design-load efficiencies averaged across a range of manufacturers is assumed for natural-gas-fired power plants, due to their dynamic mode of operation. Design-load efficiencies are 58.5 per cent for natural-gas-fired combined-cycle power-generating plants, and 36.5 per cent for open gas-turbines. A specific fuel consumption of 3.3 litres of diesel equivalent or 1 kg of hydrogen per 100 km is assumed, on the basis of the present-day development status, for fuel-cell-propelled cars. Assumed annual mileage for cars is 11,400 km. Light commercial vehicles and buses are evaluated on the basis of a classification contained in the GermanHy study.

Energy and CO_2 balances

The above energy concept makes it possible both to cover the vertical grid load of a total of 488 TWh on a time-dependent basis and also supply transport with 5.4 million tons of hydrogen, equating to 257 TWh of wind power. On the power-grid side, the amount of natural gas currently used for electricity generation suffices to cover the residual load. The hydrogen generated can be used among other things to operate 28 million cars.

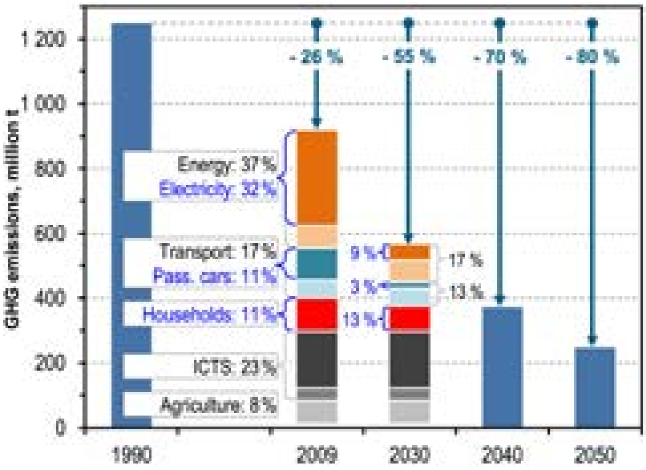

Figure 1.5: Contributions to reducing CO_2 emissions (ICTS: Industry, Commerce, Trade, Services)

A total of 697 million tons of CO_2, equating to 55 per cent, can be saved compared to 1990 when the overall reduction of 26.5 per cent already achieved between 1990 and 2009 is taken into account (Figure 1.5). Emissions of 567 million tons of CO_2 equivalent remain. The emission target for 2030 can thus already be achieved by means of the proposed provisions. Further reductions are technically possible, but must be assessed both for their feasibility and for their economic effects.

Cost estimate
A comparative cost estimate indicates that it is also economically more rational to replace petroleum-based fuels with hydrogen rather than with natural gas. Current gasoline costs at the filling station of 8 ct/kWh (70 ct/l), not including taxes, are stated as a benchmark for evaluation of the fuel option in Figure 1.6. The "permissible" costs for hydrogen at the filling station amount correspondingly to 16 ct/kWh when the above-mentioned consumption benefit is assumed. Hydrogen costs at the filling station of 11 ct/kWh can now be achieved via the central natural-gas reforming route. On the basis of the energy concept examined here, the estimated costs are around 25 per cent above the benchmark in the case of the use of electrolysis.

The cost appraisal for the "Feed-in into the natural gas grid" scenario clearly illustrates that specific costs are higher by a factor of 3.8 than those for natural gas, even in the case of direct feed-in of hydrogen. This factor actually rises to 4.7 in the case of preceding methanation. Since the variable energy costs in these scenarios are already significantly above the costs of the energy source to be replaced, economically rational feed-in of hydrogen or methane into the natural gas grid cannot at present be foreseen.

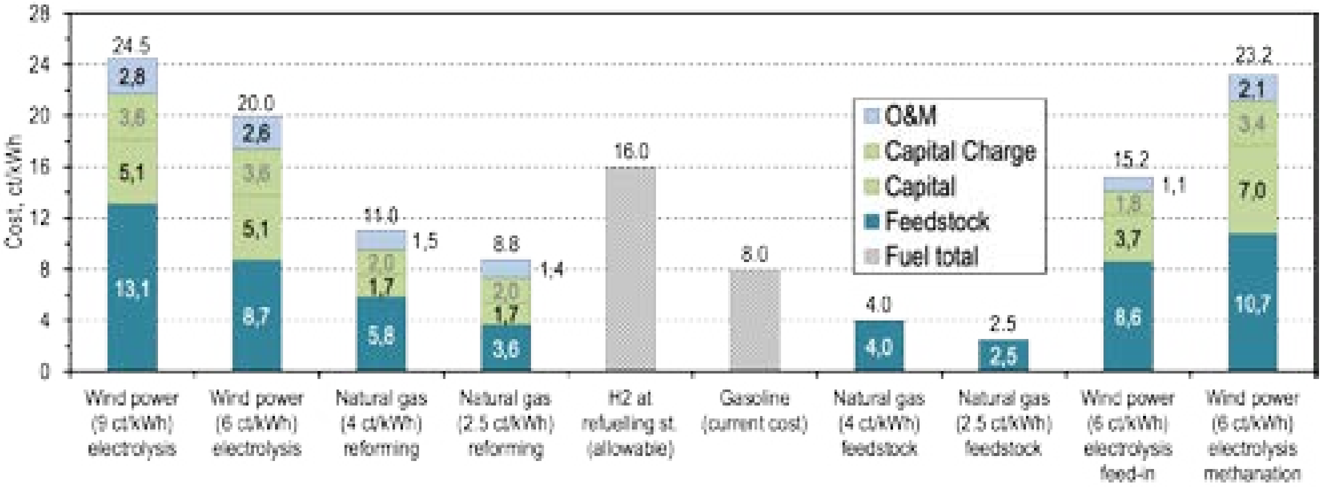

Figure 1.6: Cost appraisal of various options for the use of hydrogen

This option offers, on the one hand, the largest CO_2 savings compared to the above-mentioned utilisation alternatives (use of hydrogen for re-electrification, direct feed-in into the natural gas grid or feed-in of methane after methanation). It is, on the other hand, also the most rational alternative in economic terms, since the reference costs on the fuel market are significantly higher than in the field of utilisation of natural gas (source: Stolten/Grube/Mergel (2012)).

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2 The production of hydrogen

The hydrogen nowadays produced for the chemical industry originates essentially from the reforming of natural gas and from the electrolysis of water. These processes even now supply sufficient hydrogen for industry and for the first fuel cell applications. New process developments will in future be necessary in order to provide enough hydrogen for the energy market, however. These will include conceptual solutions based on wind and solar energy. The electricity thus generated will be used for the generation of hydrogen in electrolysers, which are currently largely utilised for the production of chlorine and are operated predominantly using fossil-generated electricity. New electrolyser developments will help in the utilisation of the intermittent surplus availability of renewably generated electricity yielded in the context of the energy turnaround for the production of hydrogen, and thus either for direct use or for energy storage. Biomass (solar energy stored via photosynthesis), the digester gases generated in sewage treatment plants and added organic byproducts can also be converted to hydrogen.

Reforming of natural gas

Hydrogen is nowadays produced primarily by means of the reforming of natural gas (heterogeneous catalytic steam reforming of methane), and also by means of the gasification of coal or biomass with the addition of water and, where necessary, oxygen (air), as reactants. The initial product of the reforming of natural gas is a so-called “synthesis gas” (hydrogen, carbon monoxide, carbon dioxide, steam and residual hydrocarbons). Carbon monoxide can be further transformed via a conversion reaction with water to obtain hydrogen and carbon dioxide. Hydrogen is separated out of the gas mixture by means of absorption, adsorption or with membranes.

Figure 2.1: Air Liquide hydrogen production plant (source: AIR LIQUIDE Deutschland GmbH)

Central reforming
AIR LIQUIDE Deutschland GmbH operates at Marl, NRW, Europe’s largest hydrogen packing and shipment centre. At the Marl “Chemiepark”, hydrogen is mainly produced using steam reformers (Figure 2.1) and then compressed to up to 300 bar.

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Electrolysis of water

The electrochemical production of hydrogen by means of the electrolysis of water is a relatively old technological process and has been globally established for more than a century. Around the world, only approx. 4 per cent of hydrogen needs is produced by means of electrolysis, due to the at present higher production costs compared to the use of fossil energy sources (e.g. natural gas and coal). In future energy systems, in which renewable energy sources are to be an important component of the energy mix, hydrogen will play a significant role as a storage medium and energy source for transport, inter alia, however.

Electrochemical splitting of water by means of electrolysis consists of two sub-reactions, which are separated by an ion-conducting electrolyte. One can differentiate between three relevant water-electrolysis processes, depending on the electrolyte used. These are summarised in Figure 2.2, which shows their respective sub-reactions at the anode and cathode, the typical temperature ranges and the ions for the corresponding charge transfer:

- Alkaline electrolysis using a liquid basic electrolyte
- Acidic PEM electrolysis, using a proton-conducting polymeric solid electrolyte
- High temperature electrolysis, using a solid oxide as the electrolyte

Alkaline electrolysers
Commercial plants are currently based only on alkaline electrolysis (various series of which have been available with capacities of up to approx. 750 Nm³/h hydrogen for several decades, see Figure 2.2 left) and PEM electrolysis (only approx. 20 years of plant development, and therefore only few commercial plants, of < 65 Nm³/h, available on the market). Alkaline electrolysers generally operate using a solution of KOH in water. The voltage efficiency of the stack of commercial systems is around 62 to 82 per cent in relation to the higher heating value.

Only a few thousand plants have been completed since the introduction of water electrolysis more than one hundred years ago, however. The state-of-the-art in large-scale electrolysis installations has changed only marginally during the past forty years, due to this comparatively low level of activity.

PEM electrolysers
Plant development on PEM electrolysis, featuring proton-conducting membranes (Figure 2.2, centre) has been going on only for twenty years, with the result that only a few commercial plants, for industrial niche applications (e.g. local production of high-purity hydrogen for semiconductor production and for the glass industry) are available. Unlike alkaline electrolysis of water, the PEM process uses electrodes consisting of platinum-group metals. The voltage efficiency is approx. 67 to 82 per cent but with significantly higher current densities (0.6 to 2.0 A/cm²) compared to alkaline electrolysis of water. A service-life of up to 60,000 h is stated for the stacks in operational systems.

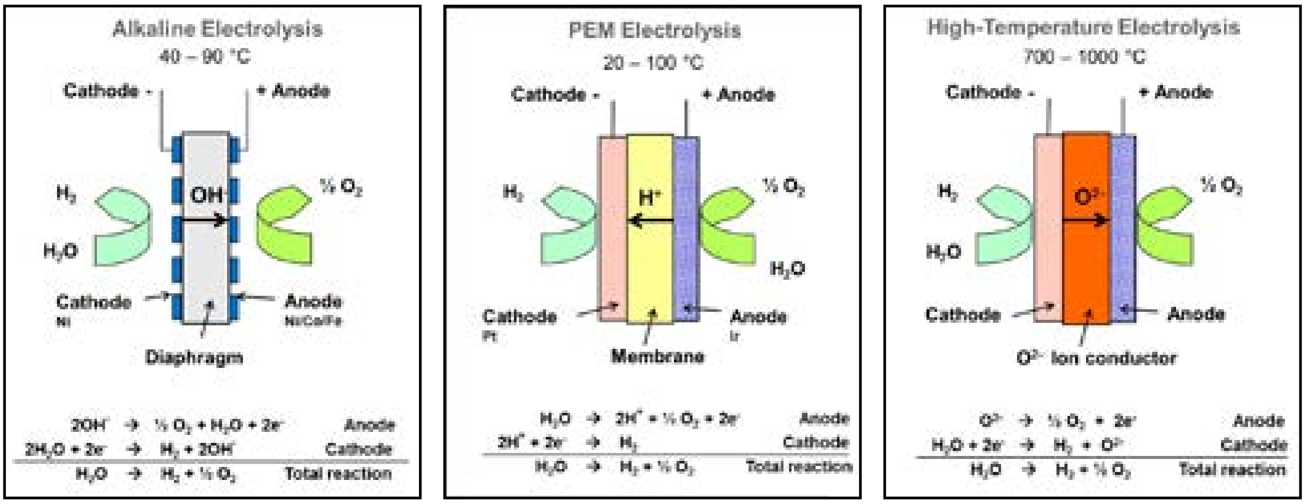

Figure 2.2: The principles of the various types of water electrolysis

Hydrogen for load regulation

The fluctuating availability of renewable energy (in the form, for example, of wind power) confronts the process-engineering of the particular electrolysis technologies with special challenges, since the electrolyser is used to provide reserve capacities, and is thus operated at greatly fluctuating output levels and with frequent interruptions, due to the lack of power input. Part-load behaviour is a source of particular problems in the case of alkaline electrolysers, due to increasing impurities in the gas. The lower part-load range of alkaline electrolysis installations is, for example, only 20 to 40 per cent of nominal load, since the concentration of extraneous gas and, in particular, of H_2 in O_2, can very quickly reach a critical level of, for example, 2 per cent, at which point the system must be shut down for safety reasons. PEM electrolysis has a larger part-load range than alkaline electrolysis. In contrast to the latter, it is possible in PEM electrolysis to cut output back to a part load of 5 to 10 per cent. The two commercially available electrolysis technologies thus both have their advantages and their drawbacks (see Table 2.1).

Table 2.1: Comparative assessment of alkaline and PEM electrolysis

Alkaline electrolysis of water	**PEM electrolysis**
Advantages ■ Established technology ■ No noble-metal catalysts ■ High long-term stability ■ Relatively low costs ■ Modules for up to 760 Nm³/h (3.4 MW)	Advantages ■ Higher power density and higher efficiency ■ Good part-load capability ■ Ability to absorb extreme overloads (determining system size) ■ Extremely fast system response for grid-stabilisation tasks ■ Compact stack design for high-pressure operation
 Source: HYDROGENICS	 Source: Proton OnSite
Challenges ■ Increasing current densities ■ Broadening the part-load operating range ■ System size and complexity (“footprint”) ■ Reduction of gas-cleaning needs ■ Overall material input (stacks currently in the ton range)	Challenges ■ Increasing long-term stability ■ Scaling-up stack and peripherals into the MW range ■ Cutting costs by reducing or replacing noble-metal catalysts and high-cost components (current collectors/separator plates)

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Hydrogen from wind energy at Anwenderzentrum h2herten GmbH

Anwenderzentrum h2herten GmbH (h2herten application centre) opened in 2009 on the site of the former Ewald coalmine and, in its first expansion stage, provides around 3000 m² of office and technology-centre space and an ideal and future-orientated working environment for companies active in the field of future energy.

The essential element in the building's equipment is the implementation of the energy and hydrogen-supply concept, based on the utilisation of renewable energy sources and on locally available wind power, in particular.

Anwenderzentrum h2herten GmbH, together with the Westfälisches Energieinstitut (Energy Institute of the Westphalia University of Applied Sciences, Gelsenkirchen), conceived this technology and commissioned Evonik GmbH for project steering in the context of an EU-wide tendering procedure.

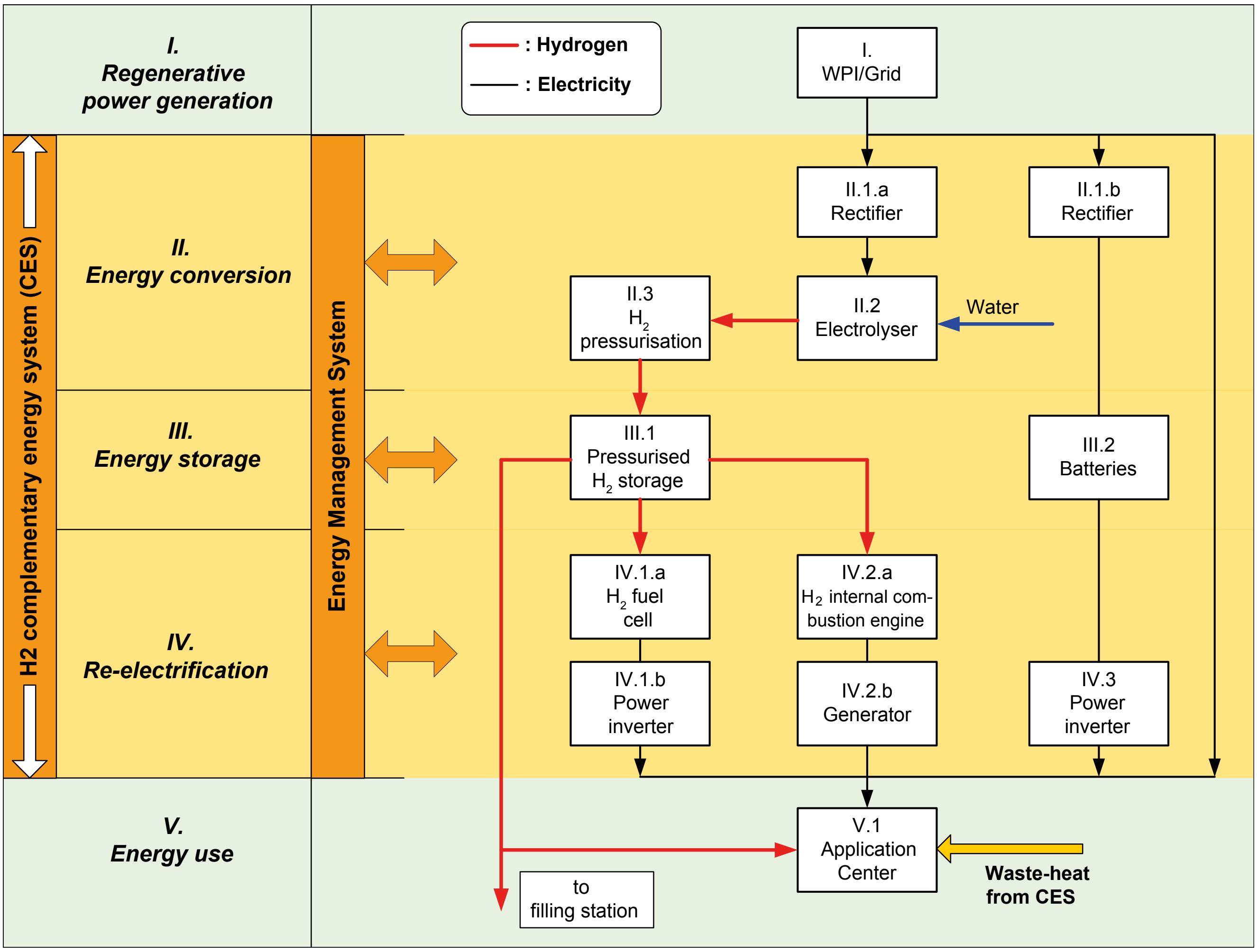

Figure 2.3: Hydrogen-based complementary energy system and peripherals

The hydrogen-based complementary energy system (CES) will perform the following tasks:

- Electrolytic production and storage of hydrogen
  - for centre operation
  - for the supply of a planned H_2 filling station and
  - for the provision of reserve capacities
- Use of temporarily stored hydrogen for re-electrification
  - for conditioning of the electricity fed in by the wind-power system (reserve capacities) and
  - for supplementary power supply to the centre in case of inadequate direct supply of regenerative power, or coverage of short-term peak demand (reserve capacities)

The combination of wind-power installation and the hydrogen energy system will largely meet the centre's hydrogen requirement and annual power needs, totalling 200,000 kWh_e, with zero CO_2 emissions and high supply quality.

The basic structure of the planned hydrogen-supply and complementary energy system (CES) plus peripherals can be seen in the block diagram shown in Figure 2.3. The CES comprises the following three functional levels:

- Energy conversion (II):
  Conversion of AC to DC electricity via a rectifier, and to hydrogen via an electrolyser
- Energy storage (III):
  - Short-term storage of DC electricity in batteries
  - Medium- to long-term storage of hydrogen in pressurised tanks
- Re-electrification (IV):
  - Conversion of DC battery electricity to AC electricity via a power inverter
  - Conversion of hydrogen to AC electricity, either via a fuel cell and power inverter or via an H_2 internal combustion engine and a generator

Using hydrogen for operation of hydrogen-powered vehicles is also planned, in addition to its utilisation for the provision of reserve capacities. The electrolyser's output has therefore been selected in such a way that a filling station supplying "green" hydrogen to be constructed in the future near the centre can also be supplied from the anticipated surplus of wind-generated electricity.

Project partners:

Hydrogenics GmbH, Gladbeck	Electrolysis, fuel cell
Linde AG, Düsseldorf/Vienna	Compressors
Gustav-Klein GmbH, Schongau	Power electronics
Saft Industries, Nuremberg	Li ion battery
Vako GmbH, Kreuztal	H_2 storage system
Theissen GmbH, Ochtrup	Piping
Janssen GmbH, Aurich	Electrical engineering and NSP
ProPuls GmbH, Gelsenkirchen	C&I
Westfälische Hochschule, Gelsenkirchen	Scientific support
K-HyCon, Herten	Technical project management
EVONIK, Essen	Detailed engineering and project implementation

Time horizon:

Start of project:	October 2010
Commissioning:	April 2013

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Industrial hydrogen

The vision of the climate-friendly energy-route utilisation of hydrogen in the future is inseparably linked to the production of this gas using regenerative energy. The use of hydrogen generated by other means in industrial processes and of existing infrastructural elements could be a rational option for a transitional period, however. North Rhine-Westphalia offers, in its Rhine-Ruhr industrial conurbation, particularly good preconditions for such a concept, including numerous locations suitable for the energy-route use of hydrogen.

A study by the Federal State of North Rhine-Westphalia, "Options for the cost-optimised creation of an H_2 infrastructure in North Rhine-Westphalia " (source: Pastowski et al. [2009]), combines a survey of the quantity of hydrogen available in North Rhine-Westphalia with the modelling of the setting-up of a hydrogen infrastructure, emphasising the especially favourable conditions already existing in this state.

Significant sources and uses of industrial hydrogen in NRW can be found, in particular, in chlorine production, at oil refineries, and at coking plants. In some cases, hydrogen is also produced by means of reforming natural gas, for use as a chemical feedstock in other production processes. Apart from traces of mercury in the obsolescent amalgam, or brine electrolysis, process, high-purity hydrogen is yielded as a byproduct in the electrolytic production of chlorine. Current process-engineering development projects using oxygen depolarized cathode technology and first large scale applications in China and Brunsbüttel (Germany) indicate potentials for the production of chlorine with significant energy-savings but with no hydrogen byproduct in the future, however.

Figure 2.4 shows a summary of the results of a survey covering North Rhine-Westphalia. Here, chlorine-alkaline electrolysis plants account for only 16 per cent of total hydrogen production, while the share held by such facilities in the hydrogen potential for new utilisations amounts to 85 per cent. Refineries and other facilities account for more than 80 per cent of total hydrogen production, but together, contribute only 20 per cent to the potential.

In the short term, the industrial potential of 958,000 Nm^3 per day, or 350 million Nm^3 per annum, could be used to fuel around 260,000 fuel cell cars (12,000 km per year, at a consumption of 3.5 l gasoline equivalent, or 1 kg hydrogen, per 100 km) for the initial projects during the market-launch phase.

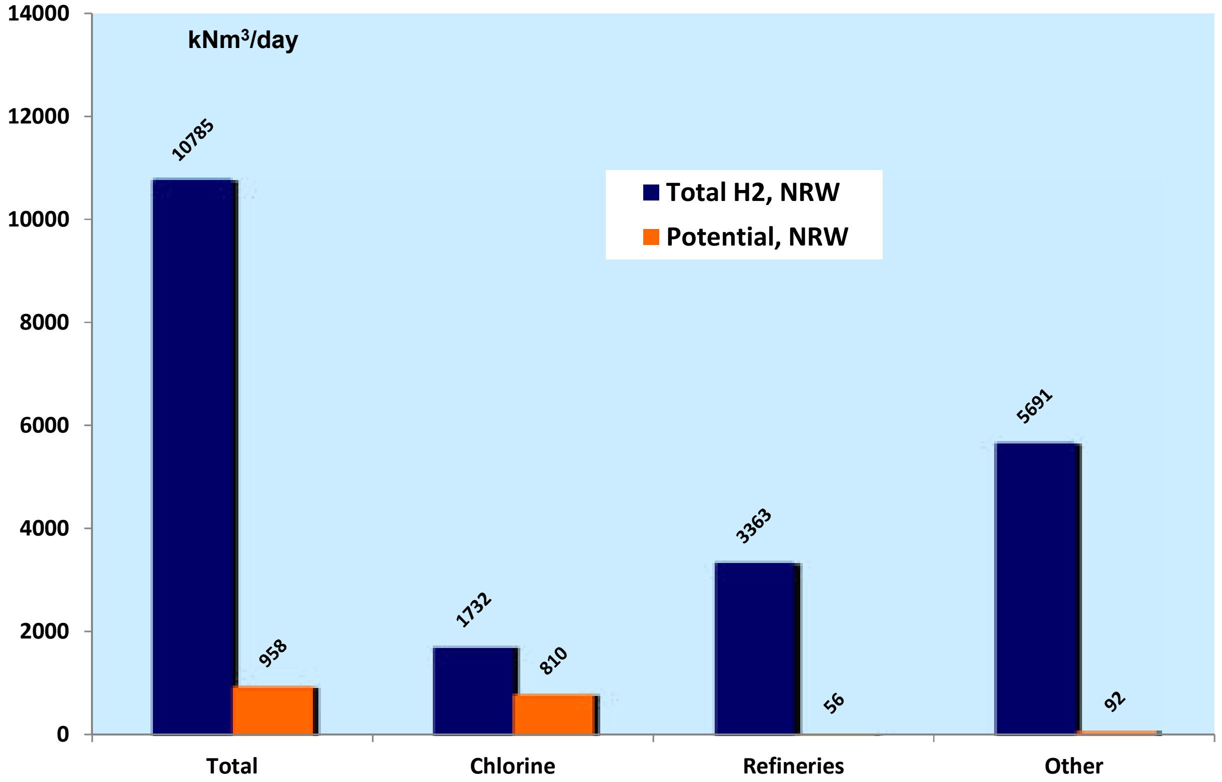

Figure 2.4: Estimate (2008) of total industrial hydrogen in North Rhine-Westphalia and hydrogen potential for new uses (source: Pastowski et al. (2009))

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Photobiological hydrogen production

Biological processes can also be used for the regenerative production of hydrogen. Certain organisms are capable of utilising the sun's energy to generate hydrogen via photosynthesis. This route is referred to as "photobiological hydrogen production". Green algae and cyanobacteria are organisms with a laboratory-proven ability to generate hydrogen under special conditions.

Under the influence of sunlight, water is split within the cell into hydrogen and oxygen. The hydrogenase (H_2ase) enzyme, which catalyses the electrons transported by the photosystem from the water-splitting process with the free protons to form hydrogen, is the decisive factor. This enzyme is activated in the green alga under low-sulphur conditions. The metabolism of the alga then changes from its normal CO_2 fixing function to hydrogen production (Figure 2.5). The problem with the green alga is the fact that hydrogenase is inactivated by oxygen, which is formed as a byproduct. For this reason, hydrogen production can take place only under anaerobic conditions, and only for extremely short periods of time. The green alga is at present capable of generating up to 2 ml of hydrogen per litre of algae suspension per hour when these limitations are taken into account.

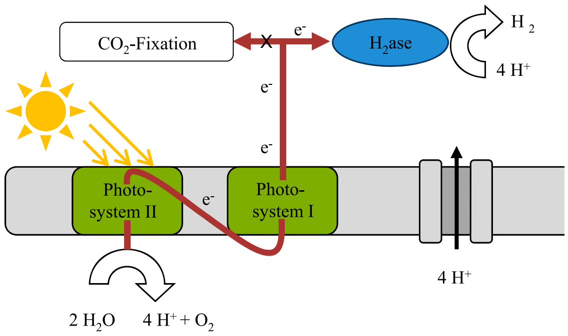

Figure 2.5: Cell (source: RUB)

Engineers and scientists from the universities of Bochum, Cologne and Berlin, and also from the Max Planck Institut, in Mülheim, are currently working on the "H_2 Design Cells" co-operation project funded by the Federal Ministry of Research in order to evaluate and improve this process. The biologists' aim is to develop, in small increments, a "design organism" which will eliminate the disadvantages of the green alga mentioned above and combine the advantages of a range of different organisms, and ultimately to generate a robust and highly effective organism. A cyanobacterium which has been genetically characterised extremely well and is also mutable and is notable, in addition, for its robustness, is to provide the basis for this new organism. Another target of this co-operation project is the further development of the current laboratory reactor (Figure 2.6) and the creation of a scaled-up, effective and cost-efficient photo-bioreactor which can also be used in commercial-scale plants for the cultivation of these organisms. The Lehrstuhl Energiesysteme and Energiewirtschaft (Chair of Energy Systems and Energy Economics) of the Ruhr University of Bochum is also investigating both the present and the scaled-up process and evaluating the concept in terms of energy, ecological and economic criteria, in order to outline development potentials and identify any weaknesses.

Knowledge gained from this project indicates that scaling-up effects and energy-savings in the process technology (solar radiation input, chemical sterilisation and more effective process technology) will reduce the energy inputs for a scaled-up reactor to a level lower than is currently needed for the laboratory reactor. The most important controlling factor, however, will be an increase in hydrogen production at least by a factor of 100. This is to be achieved via the development of the "design organism" mentioned above. Decisive advances have been made in recent years.

A research and interest alliance based on already existing German and international co-operation links was also set up last year under the name "Solar Biofuels Ruhr".

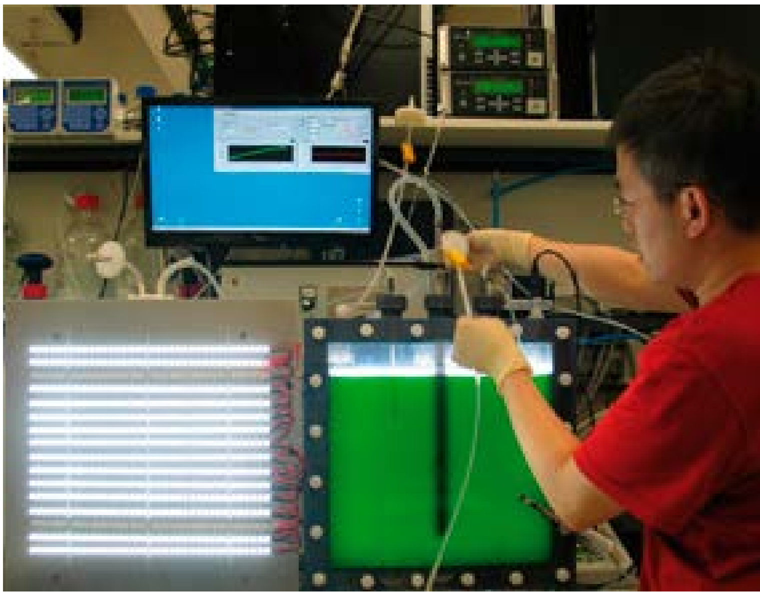

Figure 2.6: Laboratory-scale reactor (source: RUB)

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HYDROSOL – A solar-based thermochemical circuit process

A thermochemical circuit process runs CO_2-free and without any use of fossil resources if the necessary process heat is supplied using concentrated solar radiation.

In the context of the EU HYDROSOL I and HYDROSOL II projects, the DLR Solar Research team has, in co-operation with other European partners, developed and "solarised" a two-stage thermochemical circuit process in which mixed iron oxides are used as the Redox material. The reactor concept envisages the use of ceramic honeycomb structures coated with mixed iron oxide. These, on the one hand, provide the reaction surface for water splitting and act, on the other hand, as solar absorbers. The honeycomb structures are heated to the necessary process temperatures of 800 to 1200° C by means of concentrated solar radiation.

Water is split and hydrogen generated in the first of the two part-stages. In the second, the metal oxide is reduced, and thus "regenerated" for further production of hydrogen (Figure 2.7). The oxygen is fixed in the metal oxide, while the metal oxide oxidises and hydrogen is liberated.

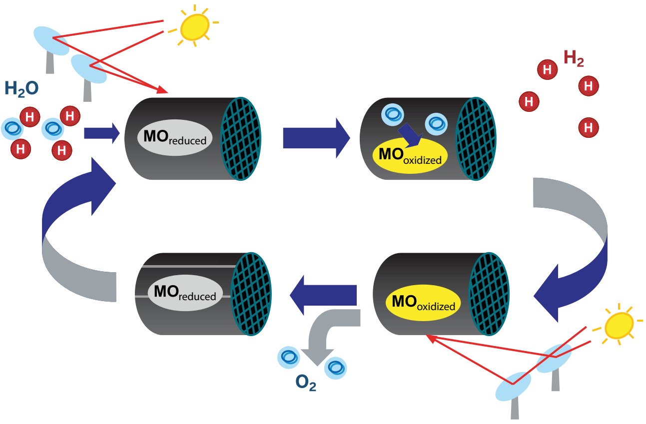

Figure 2.7: Process diagram of a two-stage circuit process (source: DLR)

Solar reactors are being developed and prepared for scale-up and use on a solar tower by means of qualification in the DLR's solar furnace in Cologne under the projects mentioned above. A 100 kW_{th} pilot system (Figure 2.8) for field testing of this process is currently in operation on the Plataforma Solar de Almería (PSA) solar tower in southern Spain. This installation has already successfully produced hydrogen in a large number of test campaigns.

Figure 2.8: Pilot installation for solar/thermochemical production of hydrogen on a solar tower (source: DLR)

The results of the test operation were used, in interaction with numerical process simulation, in the HYDROSOL 3D project to design a 1 MW pilot plant. In HYDROSOL_Plant, the fourth project of the project series, a demonstration plant is being built at PSA. The total thermal power will be 750 kW_{th}. Main aspects of the project are reactor construction, overall plant design, and control of the whole process.

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Hydrogen from wastewater treatment gas

The water industry, with its wastewater treatment plants, presents significant potentials for the introduction of a sustainable, hydrogen-based, energy infrastructure. The digester gas yielded during sludge treatment at these plants can be used as a renewable resource for the production of bio natural gas and hydrogen. Simultaneous treatment of bio-waste in the treatment plants' digestion tanks (co-fermentation) makes it possible to increase digester gas production, and thus hydrogen potential, significantly (Figure 2.9).

Emschergenossenschaft, Germany's largest wastewater treatment-plant operator, decided at an early stage to test and further develop the processing of digester gas to bio natural gas and hydrogen at its Bottrop wastewater treatment plant in the context of the "EuWaK – Natural gas and hydrogen from wastewater treatment plants" demonstration project.

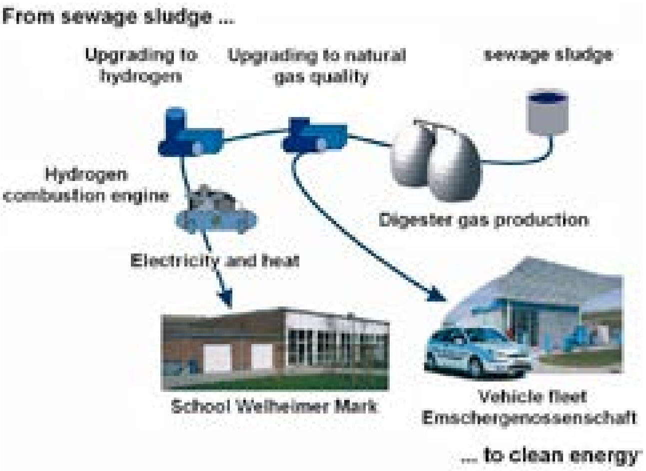

Figure 2.9: System components: "EuWaK – Natural gas and hydrogen from wastewater treatment plants" at the Bottrop wastewater treatment facility (source: EuWaK)

The partners co-operating with Emschergenossenschaft on the development and implementation of this project are Tuttahs & Meyer Ingenieurgesellschaft für Wasser-, Abwasser- und Abfallwirtschaft mbH (T&M), Forschungsinstitut für Wasser- und Abfallwirtschaft (Research Institute for Water and Waste Management, FiW) of the RWTH Aachen University, Ingenieurbüro Redlich und Partner GmbH (IBR) and the City of Bottrop.

Under this pilot project, digester gas is firstly processed into bio natural gas and hydrogen. A side-stream of the bio natural gas generated is diverted off and used to fuel twenty-four company-owned natural-gas vehicles via a gas filling station (Figure 2.10). In the second stage, the remaining bio natural gas is converted in a steam reformer to hydrogen. Maximum digester gas input is around 120 Nm^3/h, while bio natural gas processing capacity is a maximum of 72 Nm^3/h, that of hydrogen 100 Nm^3/h. The hydrogen generated is fed via a pipe to a nearby school complex, where electricity and heat are generated in a CHP plant unit to supply the school with energy.

Figure 2.10: Bio natural gas filling station (source: EuWaK)

The research results indicate stable and reliable bio natural gas production and natural gas filling-station operation. Detailed analyses of the gas during operation of the hydrogen production system in 2012 confirmed the generation of high-purity hydrogen of Grade 4.0 (99.99 % vol. H_2), and even of Grade 5.0 (99.999 % vol. H_2) in individual cases, although with an overall system availability which still requires significant improvement.

This project was implemented with financial support from the state of North Rhine-Westphalia and the European Union. Experimental operation was concluded in September 2012.

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3 Hydrogen supply logistics

The logistics of hydrogen encompass all aspects, “from well to wheel” – from the primary energy source, via conditioning (liquid, gaseous), storage and transport (gas cylinders, cryogenic vessels, trailers, pipelines), up to and including the filling of vehicle tanks. The subject covers all processes taking place at the filling station: on-site electrolytic production of hydrogen, on-site reforming of natural gas, the evaporation of liquid hydrogen, or its compression for filling of high-pressure gas-storage systems. The selection of suitable logistical concepts for the supply of hydrogen is orientated around criteria that include cost-effectiveness, efficiency and environmental impact.

The use of industrial or conventionally generated hydrogen may be a rational option for a certain transitional period until there is an adequate supply of renewable energy. Supply routes for systematic applications must be comparatively analysed and evaluated on the above-mentioned criteria. The particularly important elements in the necessary infrastructure will include mobile tanker units for early applications, the hydrogen pipeline in North Rhine-Westphalia, and options for hydrogen storage. The technical preconditions for the use of hydrogen as an energy source for mobility and transport exist, but there is at present still no comprehensive and sustainable hydrogen infrastructure.

Storage of hydrogen

The storage of hydrogen is a decisive criterion for economic success in the use of hydrogen in energy-conversion systems featuring fuel cells. Extremely intensive work on the solution of the associated problems is going on around the world. Criteria such as storage efficiency, energy consumption (energy-efficiency), service-life, filling and discharge rates, mode of storage, hydrogen losses, and costs would need to be taken into account in any comprehensive evaluation of the individual systems (hydrogen tanks, storage mass, peripherals, filling/discharge). The forms of storage examined below are of particular importance: high-pressure gas storage systems, liquefied-gas storage and solid-state storage media, and also commercial-scale storage in salt caverns, as is under discussion in conjunction with the energy turnaround.

Storage-technology options

Physical storage systems
High-pressure gas (350 to 700 bar, 23 to 39 g H_2 per litre)
Tank storage density, filament-wound type up to 4.5 %wt. H_2
Liquid storage (253 °C, 1 bar, 71 g H_2 per litre)
Tank storage density with steel shell up to 6 %wt. H_2

Adsorption storage (Van-der-Waals or other sorption bonds)
e.g.: zeolites, C nanostructures, metalorganic frameworks (MOF)

Chemical storage
(Chemical compounds of H_2 with metals and non-metals)
Metal-hydride storage
Classical metal hydrides: $LaNi_5H_6 <=> LaNi_5 + 3 H_2$
Complex metal hydrides: $NaAlH_4 <=> NaH + Al + 3/2 H_2$
Chemical hydride storage
$NaBH_4 + 2 H_2O <=> 4 H_2 + NaBO_2$ (no charging with H_2 in the vehicle)
Covalent and liquid organic hydride storage
Ammonia, boranes, hydrocarbons (no charging with H_2 in the vehicle)

Underground storage facilities

Underground hydrogen storage in geological structures

The present-day high assuredness of supply for our currently coal-, oil- and natural gas-based energy industry would be inconceivable without large-scale storage facilities in underground geological formations. Germany, for example, today has natural-gas reserves sufficient for around forty-two days stored almost entirely in porous reservoirs and artificially created salt caverns. Crude oil is also stored across prolonged periods in a large number of such caverns. The transition now initiated to renewable energy sources, and to weather-dependent wind and solar energy, in particular, generates totally new demands for balancing of production and consumption. Here, too, storage facilities located in geological formations permit balancing across a range of time horizons, extending from short-term deviations from wind forecasts, via wind-calms capable of lasting several days, up to and including seasonal fluctuations and strategic reserves.

Man-made salt caverns are particularly suitable for the storage of hydrogen, since rock salt (halite) possesses extremely low permeability to gases such as hydrogen and, in addition, does not react with it. Since this form of storage – unlike porous reservoirs – consists of a capacious cavity, with an access shaft, somewhat like a large underground tank, it is particularly suited to flexible storage input and retrieval. The suitability in principle of salt caverns for the storage of hydrogen has been demonstrated in decades of practical operation in both the UK and the USA. A certain need for further development of a number of components remains, however, as a result of the higher safety standards applicable in Germany. The necessary development work can be accomplished within a rational time horizon in the context of demonstration projects.

The dimensions of such a storage cavern typically involve cavities ranging in capacity from 250,000 to 750,000 m³, with diameters of 50 to 80 m and heights extending from tens of meters up to around 100 m, depending on the thickness of the salt deposits present. Storage densities ranging from 8 to 11 kg per m³ of geometrical cavity are achieved for hydrogen, depending on the boundary conditions. For a once-only charge, a 500,000 m³ cavern thus possesses a storage capacity of 133 to 183 GWh, referred to the lower heating value (LHV) of hydrogen. The storage facility's output is thus several 100 MW, referred to the LHV, depending on access-shaft design (Figure 3.1).

The Zechstein salt eminently suitable for cavern construction occurs in the north-west of North Rhine-Westphalia at a depth suitable for such projects. The Xanten and Epe (near Gronau) underground-cavern storage facilities are located in this region, the latter being one of Germany's largest salt-cavern gas-storage facilities. Part of Germany's strategic oil reserves is also stored here.

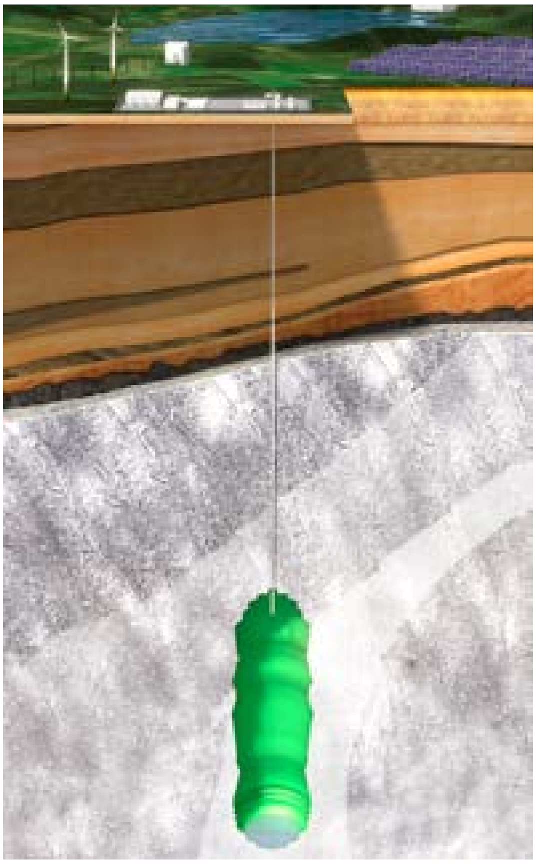

Figure 3.1: Storage cavern in Zechstein salt with a hydrogen capacity of up to 200 GWh (source: KBB)

This region provides good prospects for the installation of a hydrogen storage facility, in view of the already existing infrastructure for the creation of caverns and the potentials for sale of the brine yielded during cavern construction. Costs and time-input would thus be significantly lower than in the case of a new, "greenfield" location. The development of a new storage-facility location can take a good ten years, as a consequence of the extensive planning, approval and exploration activities that are necessary.

Near to Epe there is also a feed-in point for offshore wind power (plus a connection to the existing hydrogen pipeline in the Ruhr area), with the result that hydrogen could be produced here electrolytically from renewable energy sources.

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High-pressure gas storage

The fundamental challenge in the storage and use of hydrogen is its low energy density. Compression, to increase this density, and storage of hydrogen gas at high pressure, is an obvious and technologically relatively simple solution to increase the quantity of energy stored in a system. Gaseous hydrogen is compressed and transferred to a pressurised gas vessel with a valve, of dimensions suitable for the absorption of the powerful forces resulting from the high internal pressure. The energy input for compression is 7 (250 bar) to 9 (700 bar) per cent of the hydrogen energy to be compressed, and is supplied in the form of electricity.

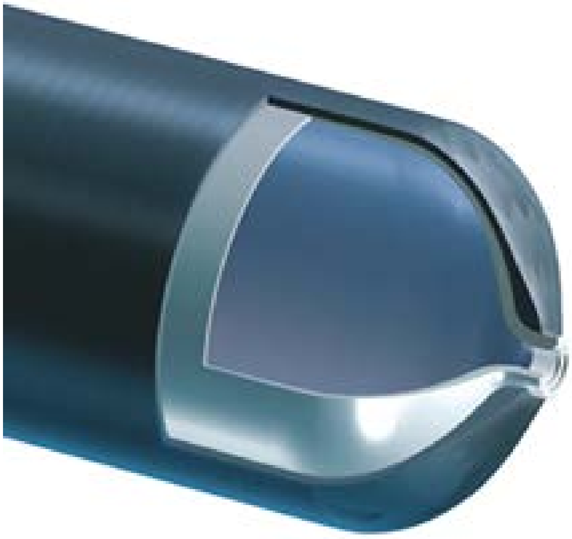

Figure 3.2: Type 3 hydrogen cylinder (source: Dynetek Europe GmbH)

Four different types of high-pressure gas storage facilities approved in the relevant codes and standards can be differentiated in principle: classical (industrial) gas cylinders are made of steel, and are consequently extremely heavy (Type 1 cylinder). In the case of the hoop wrapped Type 2 cylinders, the cylindrical section is reinforced by a filament winding which bears around 50 per cent of the load, thus permitting a certain weight-saving. Ultimately, only lightweight fully wrapped composite cylinders (Type 3 or Type 4 cylinders) can be considered for storage of hydrogen for mobile applications which, of course, make their own special demands in terms of weight and space.

These tank types incorporate a complete outer shell consisting of high-tensile fibre-composite material. Type 4 tanks are all-plastic tanks with a plastic liner, whereas Type 3 tanks are based on a metal liner (Figure 3.2). Both variants exhibit similar weight characteristics. These designs permit weight savings of some 70 per cent compared to “classical” steel tanks.

Type 3 tanks have a number of advantages over the all-plastic designs, however: for weight reasons, the metal liner is extremely thin, but nonetheless prevents the permeation of hydrogen. Particularly thin-walled design, and thus the achievement of the greatest storage efficiency for the given structural volume, is possible in Type 3 tanks, since the liner bears part of the load. Other benefits include dimensional flexibility in the available tank sizes, and suitability for high-speed filling. The Type 4 tank, on the other hand, scores with its lower price, since the plastic inner vessel can be produced extremely cost-efficiently in medium- to large-scale series. Large numbers of such composite tanks are in use even now in natural-gas-powered vehicles (pressure: 200 bar); their popularity is set to increase even further in hydrogen-powered bus (Figure 3.3) and car applications, as a result of the targeted increase in operating pressure from 350 to 700 bar. At its Ratingen plant, Dynetek produces composite tanks for pressures ranging from 200 bar to 700 bar. Customised storage systems are later to be developed, installed and supplied ready for installation.

Figure 3.3: Hydrogen tanks mounted on RVK’s APTS-Phileas fuel cell bus (350 bar, Type 3 tank with aluminium liner, 8 x 205 litre) (source: Dynetek Europe GmbH)

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Liquefied gas storage facilities

The storage of hydrogen as a liquid at -253 °C is not a new technology, and has been used in the gas industry since as long ago as the early 20th century.

A liquid-hydrogen tank consists essentially of two vessels: the outer tank is exposed to atmospheric pressure, and the inner tank, under high-grade vacuum, to internal pressure loads. Such tanks are nowadays nearly always extruded from austenitic stainless steel (Figure 3.4).

One challenge in the storage of liquid hydrogen is the gradual evaporation of the stored product as a result of the ingress of heat from the exterior (by conduction, convection and radiation). The so-called "boil-off" effect (evaporation of the gas) cannot be prevented if no gas is discharged for a long period. The time until boil-off occurs can be decisively prolonged by means of sophisticated insulation systems, active cooling and/or a combination of a liquid and pressurised storage mode. In addition, recent developments aim at using the "boiled off" gas for energy purposes directly, via a fuel cell, or storing it for later use.

Figure 3.4: Section through a liquid-hydrogen storage facility (source: Linde AG)

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Solid-state storage media

Solid-state storage media (metal and non-metal hydride storage systems, and carbon-based solid-state storage media, or hybrids of these types) provide a third alternative for the storage of hydrogen, in addition to pressurised and liquid-hydrogen storage facilities. The known reversible hydride systems store up to 1.5 per cent by weight of hydrogen at room temperature. Complex hydrides with an H_2 storage capacity of up to 5.5 per cent by weight have been under investigation for a number of years now: reversible hydride compounds (recharging at hydrogen pressure possible, e.g. $NaAlH_4$), on the one hand, and non-reversible hydrides (recharging at hydrogen pressure not possible; chemical reactions necessary for regeneration as, for example, in the case of $NaBH_4$), on the other hand. Reversible hydride systems are preferred for mobile applications.

The use of metal hydrides as hydrogen storage media in the mobility sector is limited by the needs for high-speed hydration. Recharging (tanking-up) should take place under the following conditions: pressures of $p < 50$ bar, temperatures of $T < 100$ °C and times of $t < 10$ min. No systems which meet these requirements and also offer a sufficiently large storage capacity are known at present, however.

The Max-Planck-Institut für Kohlenforschung (Max Planck Institute for Coal Research) in Mülheim an der Ruhr performs fundamental research in organic and metalorganic chemistry, homogeneous and heterogeneous catalysis and theoretical chemistry, with the aim of developing new methods for selective, environmentally friendly conversion reactions.

New materials based on complex aluminium hydrides are being researched and further developed for the storage of hydrogen. Complex aluminium hydrides based on $NaAlH_4$ achieve reversible storage capacities of 5 per cent hydrogen by weight (1 g of storage medium releases around 600 ml of hydrogen), but materials with higher hydrogen contents are needed for mobile applications.

The rate of release and charging of the media with hydrogen can be varied within a wide range via the selection of suitable catalysts. The properties of the storage medium can thus be matched to the needs of fuel cells. These solid-state storage media are being developed in close co-operation with vehicle manufacturers. Solutions for the integration of solid-state storage media and fuel cells in complete systems suitable for practical use in the 200 W_{el}

range are being developed with Zentrum für BrennstoffzellenTechnik ZBT GmbH (The fuel cell research center ZBT GmbH) and the Institut für Energie- und Umwelttechnik (Institute of Energy and Environmental Technology – IUTA) (Figure 3.5).

Metal hydrides store not only hydrogen reversibly, but also large quantities of heat. This heat can be added in case of a heat surplus (yielding hydrogen), then retrieved and used again at the same temperature, with no losses, when heat is needed. Materials and systems based on Mg compounds are being developed for the 300 to 600 °C temperature range.

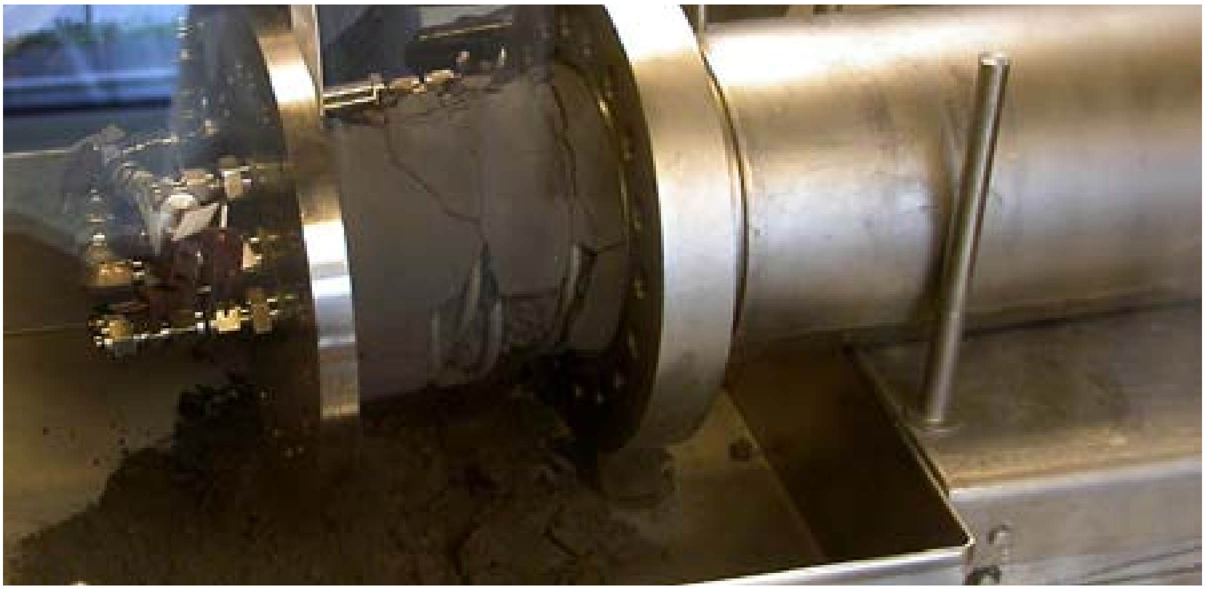

Figure 3.5: Example of a storage tank functioning as an H_2 source for an HT PEM fuel cell (Note: opened storage tank for 3 kg $NaAlH_4$; construction and development as part of AiF project 247ZN, co-operation partners: MPI Mülheim, ZBT Duisburg, IUTA Duisburg)

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Transporting hydrogen: Distribution centre and hydrogen pipeline

AIR LIQUIDE Deutschland GmbH operates in Marl Europe's largest hydrogen distribution centre. At the Marl Chemiepark, hydrogen is mainly generated using steam reformers, and then compressed to up to 300 bar. Side streams of hydrogen supply production facilities at the Chemiepark, the distribution centre, and the pipeline. Hydrogen trailers with an operating pressure of 200 bar and a capacity of 3500 to 7500 m³ (290 to 625 kg), steel cylinders and cylinder batteries with operating pressures of 200 and 300 bar, are filled at the distribution centre. Around 15,000 such trailer vehicles and a large number of cylinders and cylinder batteries are filled every year. Marl is also the starting point of Germany's longest hydrogen pipeline, which has a total length of some 240 kilometres (with terminals at Castrop-Rauxel and Leverkusen, plus connections to Krefeld and Oberhausen, see Figure 3.6).

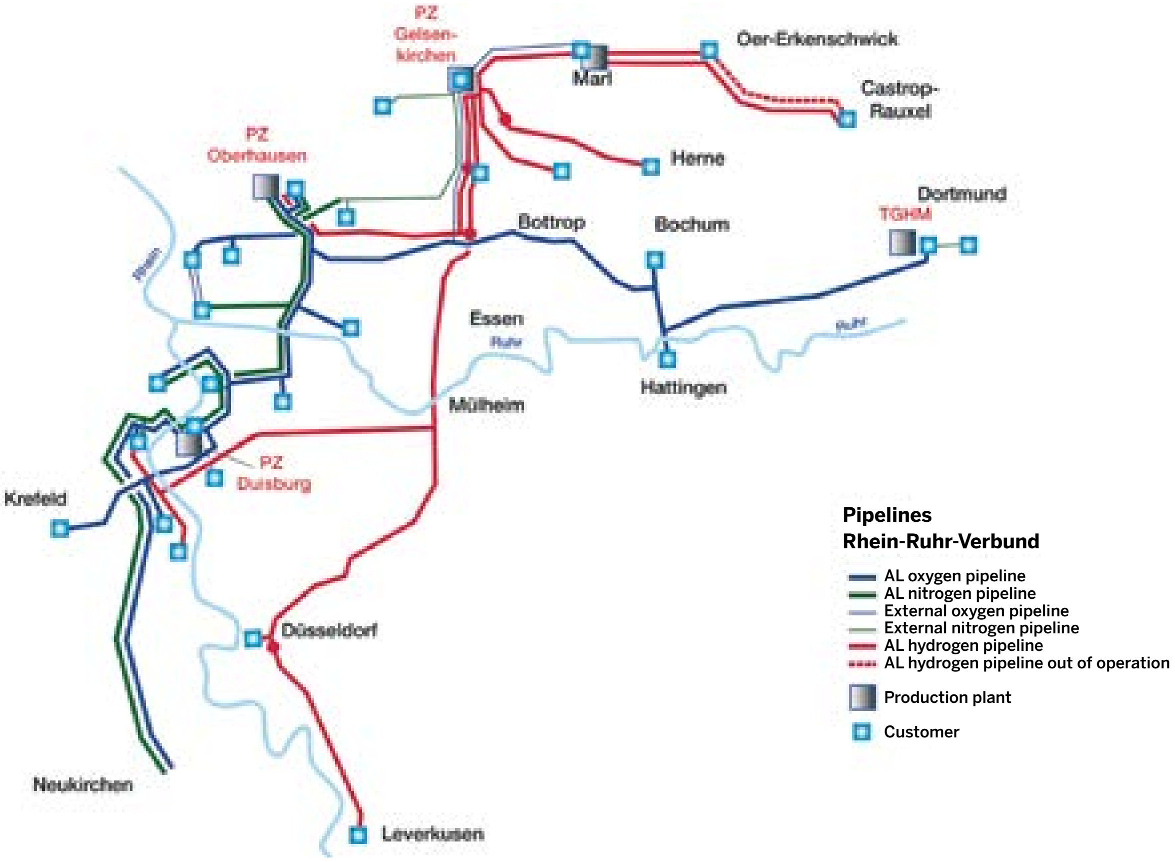

Figure 3.6: The hydrogen pipeline network (240 km) (source: after AIR LIQUIDE Deutschland GmbH)

The pipeline can convey a maximum of 40,000 m^3 of hydrogen per hour, at operating pressures of up to 25 bar. This pipeline provides safe, reliable and rationally priced transmission of hydrogen with high assuredness of supply. Consumption peaks and troughs at individual customers can be absorbed; industrial hydrogen can also be fed in. This pipeline may in the future be an essential element in a rational-cost hydrogen infrastructure for mobile fuel cell applications in North Rhine-Westphalia. Special composite cylinders (capacity: 2 litres, pressure: 700 bar) can be filled at a filling installation developed as part of the European HyChain project supported by North Rhine-Westphalia (www.hychain.org).

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Fuelling with hydrogen: Filling-station technology

In addition to offering the ecological benefits of zero CO_2 emissions, hydrogen is also a highly promising source of energy from a technological viewpoint. Its properties as the “lightest” and least dense element in the universe must also be taken into account in its storage and handling if it is to succeed commercially as a vehicle fuel, however.

Hydrogen will be supplied to the filling station either as a cryogenic liquid at -253 °C (liquefied hydrogen, LH_2) or in gaseous form at pressures of 200 to 500 bar (compressed gaseous hydrogen, or CGH_2) and transferred to the corresponding storage tanks. It can also be generated on site at the filling station by means of electrolysis or steam reforming, however. Since vehicles have only a restricted amount of space for their hydrogen tanks, as much energy as possible must be stored in the smallest possible space. The hydrogen is therefore compressed at the filling station. The fuel cell vehicle can then be tanked up with gaseous hydrogen.

The compressor technology is the central element of any hydrogen filling station. There are, in principle, two different procedures: gaseous hydrogen can, on the one hand, be compressed to up to 900 bar using various compressor principles, such as non-lubricated, diaphragm and ionic types, the latter being a technology specially developed by Linde AG for this application. Liquefied hydrogen can, on the other hand, be further compressed by means of cryogenic pump technology to up to 900 bar, then heated to -40 °C and metered in gaseous form. This technology is a particularly interesting option where demand is high. The cryogenic pump is also part of Linde AG's technology portfolio. It is the most efficient system, with an extremely small footprint and exceptionally low energy consumption (Figure 3.7).

Figure 3.7: Cryogenic pump system (source: Linde AG)

Hydrogen is stored in gaseous form at 700 bar in fuel cell cars, whereas pressures of 350 bar are the norm in fuel cell buses. The gas is transferred at 900 bar at the filling-station pump, this providing the differential pressure necessary to assure complete filling of the vehicle's hydrogen tank. The tanks of cars can currently hold up to seven kilograms of hydrogen, permitting a range of up to 700 kilometres.

The technology as such, and also the storage, compression and filling operations, are now so mature that globally applicable uniform fuelling standards for commercial use have been evolved (SAE Standard 2601). There are, even now, standardised solutions for the filling operation for fuel cell vehicles and for the use of the fuel-pump nozzle, this being very similar to that for fuelling with natural gas. Filling times are, as in the case of conventional fuels, also only around three minutes, the only difference being that the consumer will, in future, no longer be charged in litres, but in kilograms, instead.

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NRW's first public hydrogen filling station for cars

The expansion of the filling-station infrastructure must be further accelerated, to permit the market launch of hydrogen-powered vehicles in Germany. North Rhine-Westphalia's first public hydrogen filling station for cars, opened by AIR LIQUIDE on Höherweg, in Düsseldorf, in early September 2012, is yet another milestone on the road to completion of this undertaking (Figure 3.8).

The Höherweg filling station, financially supported by the NRW environment ministry, is part of the "Clean Energy Partnership" (CEP) lighthouse project which, at that time, was receiving support from the National Innovation Programme for Hydrogen and Fuel Cell Technology (NIP). The filling-station project is the starting point for the other CEP activities in NRW, Germany's most populous federal state.

Figure 3.8: Overall view of the H_2 filling station in Düsseldorf (source: AIR LIQUIDE Deutschland GmbH)

Up to fifty cars and light commercial vehicles can be tanked up at 700 and 350 bar in Düsseldorf each day. Fuelling of buses using a separate 350 bar dispenser will also be possible in the second expansion stage. This filling station is unmanned, but is remote monitored. The hydrogen is precooled down to -40 °C using liquid nitrogen, which is stored in a tank on the filling-station site, in order to achieve fuelling times comparable to those for conventional vehicles of around 3 to 5 minutes at 700 bar (see Fig. 3.9).

The hydrogen is stored at the filling station at a storage pressure of 200 bar in four high-capacity cylinder batteries, each consisting of sixty-eight standard 50 litre steel cylinders, amounting to a total capacity of around 200 kg. The cylinder batteries are permanently installed, and are refilled by tanker trailers at regular intervals. The gas is compressed using a two-stage diaphragm compressor, and then temporarily stored at 420 or 850 bar in two special high-pressure storage installations.

Together with the Federal Transport Ministry, Air Liquide and other leading industrial enterprises co-operating in the Clean Energy Partnership have entered into a binding declaration of intent to construct a network of fifty hydrogen filling stations by 2015.

NRW is a central focus of Air Liquide's hydrogen activities, since the company operates a 240 km long hydrogen pipeline in the Rhine-Ruhr conurbation and, at Marl, Europe's largest hydrogen distribution centre. Three non-public hydrogen filling stations have already been completed in the Rhine-Ruhr region.

Figure 3.9: Vehicle fuelling

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4 Hydrogen in use

In addition to its classical use in the chemical industry, hydrogen can be utilised in a broad range of stationary, mobile and portable energy applications. Engines, turbines and, above all, fuel cells, are being developed to operate as highly efficient electrochemical energy converters for the future use of hydrogen as an energy source.

Fuel cells generate electricity and heat directly from hydrogen, hydrogen-containing synthesis gases, and also from methanol. The corresponding synthesis gases may originate from natural gas, propane, diesel oil, kerosene, methanol, biomass, and also from coal. Decentralised use of hydrogen – either locally or for onboard supply in vehicles – is often linked to the availability of a hydrocarbon-containing energy source, such as natural gas, propane or diesel oil, and the associated preparation process for the production of a hydrogen-containing synthesis gas.

The high electrical efficiency of generating electricity in fuel cells makes it possible to achieve lower emissions (GHG, CO, C_nH_m, NO_x and particulates emissions) compared to conventional energy conversion systems. Fuel cell systems are eminently suitable for supply of power and heat (combined heat and power cogeneration) to buildings and for onboard supply of energy in vehicles. The use of fuel cell technology thus offers numerous advantages over the present-day energy-supply structure.

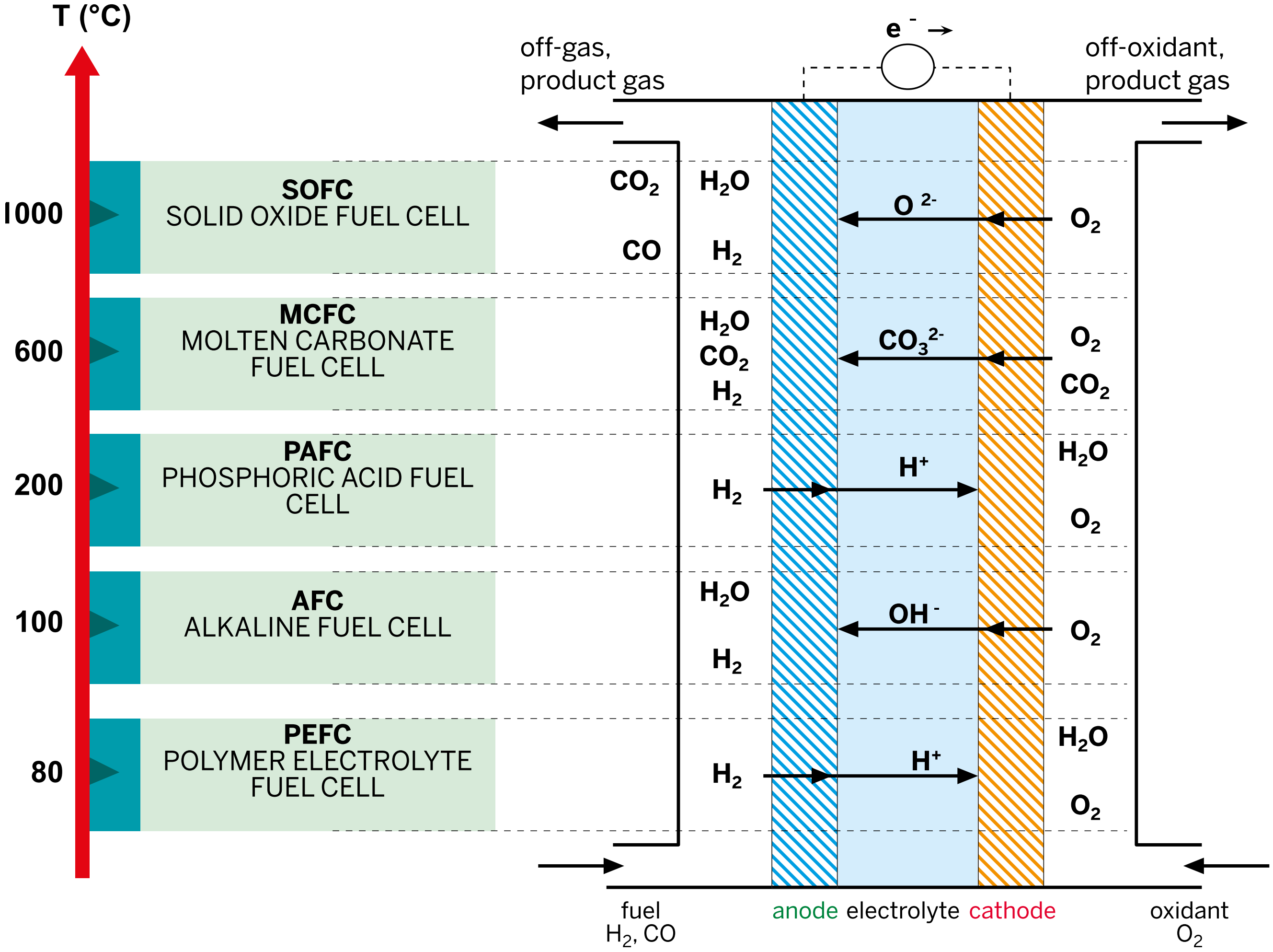

Figure 4.1: Classification of fuel cells (not including DMFC for direct use of methanol) (source: Fuel Cell and Hydrogen Network NRW)

Fuel cells – an overview

Several different fuel cell types, which are differentiated by their electrolytes, operating temperatures and reactant gases, are currently under development: alkaline fuel cells (AFC), membrane fuel cells (PEMFC or PEFC), direct methanol fuel cells (DMFC), phosphoric-acid fuel cells (PAFC), molten-carbonate fuel cells (MCFC), and solid-oxide fuel cells (SOFC). The specific properties of these types give rise to a range of different applications. Differing fuel cell types (Figure 4.1), and corresponding energy sources, ranging from hydrogen up to and including liquid and gaseous mixtures of hydrocarbons, result in extremely diverse process-engineering efforts for providing fuel gas upstream the fuel cell system and also, all in all, exhibit differing efficiencies and power-to-heat ratios for the simultaneous generation of electricity and heat.

The example of a PEMFC may serve to explain the function and structure of fuel cells (see Figure 4.1, PEFC). A PEMFC consists of an anode and a cathode, which contain the electrocatalyst and are directly pressed on to the electrolyte membrane. Hydrogen (H_2) flows on to the anode and is split on the catalyst into atomic hydrogen (H). The hydrogen atoms yield their electrons (e^-) via an interconnector to an electric circuit. The remaining hydrogen nuclei (protons, H^+) migrate through the electrolyte membrane to the cathode side, on to which air flows. Via an interconnector, air oxygen (O_2) absorbs electrons from the electric circuit, resulting in the generation of O^{2-}. The oxygen ions then react with the protons to form water (H_2O), which is discharged from the cell.

The flow of electrons through the electric circuit generates electrical power. The remaining energy released during this chemical process is present in the form of heat. In order to obtain a voltage suitable for use, a number of fuel cells are connected in series and configured in the form of a so-called stack. The PEMFC operates at temperatures of 60 to 80 °C, as a so-called low-temperature membrane fuel cell (LT PEM). Unlike LT PEMs, high-temperature membrane fuel cells (HT PEMs) can be operated in the 130 to 200 °C temperature range with a higher CO tolerance and simplified water and heat management.

A fuel cell system with the membrane-electrode arrangement (MEA), diffusion layer, bipolar plates (between the cells), endplates and seals, needs augmentation with an electrical system, auxiliary systems, air supply and, where necessary, a fuel system. Special processes for providing hydrogen, involving a reformer and gas after-treatment, are necessary when energy sources such as methanol, diesel oil, kerosene or natural gas are used.

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PEM developments

Polymer-electrolyte-membrane fuel cells (PEMFC or PEFC) are essential elements in an efficient future energy-conversion technology. Potential applications range from mobile use, in motor-vehicles, for instance, via onboard power supplies, up to and including both stationary and portable service. Hydrogen or reformed hydrocarbons, which can be converted both in the classical LT PEM and, at 160 °C, in the HT PEM fuel cell, may be selected as the energy source, depending on the specific application.

Zentrum für BrennstoffzellenTechnik ZBT GmbH in Duisburg has developed for both of these energy sources – hydrogen and reformed hydrocarbons – a technology for the construction of compact membrane fuel cell stacks in both the classical low-temperature (LT) variant and for HT operation at 160 °C. Automated production processes for the necessary components and fuel cell stacks are currently under development.

An important fuel cell element, the so-called bipolar plate, has been produced on a small-series scale by means of injection moulding at the ZBT for several years now, for internal use for the manufacture of low-temperature stacks. In combination with the proton-conducting polymer membrane and the two gas-diffusion layers, bipolar plates perform a large number of decisive tasks for maintaining the electrochemical process in PEM fuel cells, including the conduction of electrical and thermal output, feed and discharge of media, and the mechanical stabilisation of the stack. Injection-moulded bipolar plates (active surface area: 50 cm^2) are used for the creation of air- or water-cooled fuel cell stacks for an output range extending from 100 to 1000 Watt (depending on the number of cells). Gräbener Maschinentechnik is developing stacks featuring extremely flat metal bipolar plates as a compact variant for use as “range extenders” in automotive applications (Figure 4.2).

Specification for the ZBT/Gräbener Maschinentechnik BREEZE LT PEM stack:

- Seven-layer MEA
- Metal bipolar plates, integrated seals
- Pressurised operation at up to 2 bar (a)
- Liquid coolant

Figure 4.2: BREEZE LT PEM fuel cell stack, 20 cells, ZBT, in co-operation with Gräbener Maschinentechnik

The HT PEM, which is based on phosphoric-acid-doped polybenzimidazole membranes, has a typical operating temperature of 160 °C. This high temperature level gives it a high CO tolerance, an advantage which makes the HT PEM predestined for use in combination with reformers. The great temperature difference between the stack and the ambient temperature is also advantageous, since the cooling system can thus be designed significantly more compact than in the case of classical PEM systems.

Systems-technology aspects (peripheral and control technology) and application techniques are major development issues. The following are typical applications for such systems and, therefore, for the Duisburg fuel cells:

- Onboard power supply (auxiliary power units [APU]) on the basis of hydrogen, LPG or methanol
- Uninterruptable power supply (UPS) for decentralised applications
- Lightweight transportation systems

Forschungszentrum Jülich (Jülich Research Center) is focussing its work in the field of HT PEMs on their use as an onboard power supply for the 5 kW range. Particularly efficient onboard power generation permits significant energy-savings in the increasing electrification of appliances and instruments in motor-vehicles, ships and aircraft. From the end-users' viewpoint, it is necessary to operate such onboard power supply systems using the fuel already available on board, thus necessitating the reforming of liquefied gas, diesel oil or kerosene (middle distillates). In combination with corresponding onboard reformer processes, the high-temperature polymer-electrolyte fuel cell makes it possible to generate electricity efficiently, particularly when the main power plant is not running.

Figure 4.3 shows the stacks in a system environment in which they are operated using diesel reformer gas.

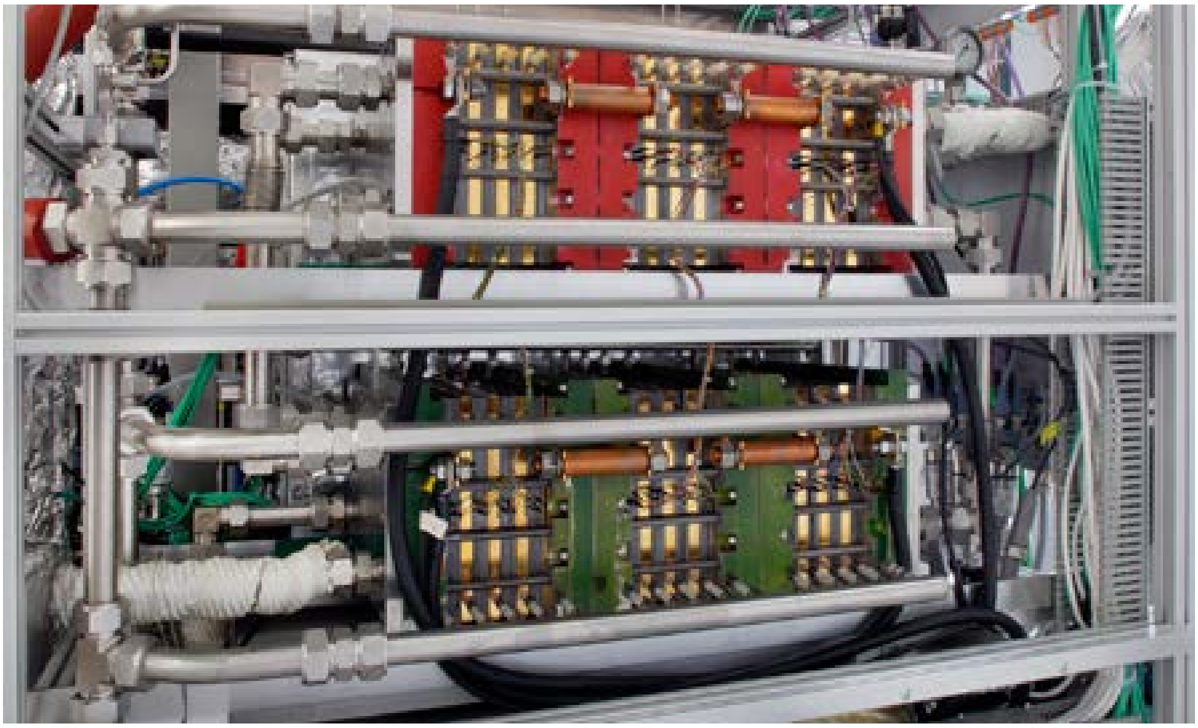

Figure 4.3: Two HT PEM stacks (up to 5.6 kW electrical output in reformate operation) (source: Forschungszentrum Jülich GmbH)

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Stationary applications

More than one third of final energy in Germany is consumed in households for space heating, hot-water generation and electrical appliances. Decentralised power generation and the simultaneous use of heat offers particular advantages, because energy losses are lowest if final energy is generated where it is to be immediately used. Combined heat and power (CHP) cogeneration at high electrical efficiencies and with low emissions is the technical challenge of the future in the creation of efficient energy supply concepts. Fuel cell technology (PEFC and SOFC, see also Figure 4.1) permits the simultaneous production of both electricity and heat in domestic heating systems with particularly low emissions. A hydrogen-rich fuel gas is generated from natural gas in a single process and then converted with air-oxygen directly to electrical current in the fuel cell. The residual heat from the overall process is fed directly to the heating circuit and utility-water storage tank. Output varies between 300 W_{el} and around 5 kW_{el}.

High-temperature fuel cells such as SOFC and MCFC are particularly suitable for combined stationary generation of electricity and heat. Since the heat is available at a high temperature level, it can also be used for the generation of process heat or, via absorption refrigeration systems, for cooling purposes as required.

The phosphoric-acid fuel cell (PAFC) is also eminently suitable for the medium output range from 50 to several hundred kW. Most operational experience has been gained using this fuel cell type; many installations have already completed 60,000 or more hours of operation. This fuel cell has conquered a new market based on fourfold benefits: the supply of suitable energy-consumers with electricity, heat, cooling and oxygen-depleted air. The latter permits active fire-safety measures, in warehouses, for example.

Potentials for PEM fuel cells are also perceived in higher-output stationary applications. They are of particular interest where large quantities of hydrogen are available, as in the case, for example, of surplus hydrogen production in chemicals plants. Fuel cell system costs, service-lives and reliability issues are the global focus of the relevant development and demonstration projects.

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Fuel cells (SOFC) – micro-CHP production in NRW

The German-Australian fuel cell manufacturer Ceramic Fuel Cells (CFC) is one of the leading developers of high-temperature fuel cells and operates production facilities for micro-CHP systems based on solid-oxide fuel cells (SOFC) at Bizzpark Oberbruch near Heinsberg. The infrastructure necessary for the production of up to 10,000 fuel cell stacks annually was set up, with investment costs of around 10 million euros, in 2009 on 900 m² of a redeveloped building with a total floor area of 4500 m². An assembly facility for the "BlueGEN" micro-CHP system, with a current capacity of around 2500 "BlueGEN" units per annum, was also commissioned here in early 2011.

Just one of these highly efficient cells – consisting of multi-layer high-tech ceramic material – generates around 12 W at 0.85 V. The single cells need to be assembled into a fuel cell stack to use this energy for practical purposes. This is the core capability of the Heinsberg facility, which is, at the same time, the first-ever semi-automated assembly plant for high-temperature fuel cell stacks of this type. After the application of the necessary glass-ceramic sealing compound, four individual cells are positioned on a mounting plate (Figure 4.4). Around fifty such mounting plates are then arranged one above the other. This process is performed at a number of individual robotic work stations. The stack is then thermally combined in a sintering furnace and finally tested in a fuel cell module.

The "BlueGEN" fuel cell system developed by CFC, with an output of up to 2 kW_{el}, has demonstrated an electrical efficiency of 60 per cent (net) in several hundred installations. Given ideal heat removal, an overall efficiency of up to 85 per cent is achieved.

The focus at its Heinsberg production plant is on robot-automated stack production, the manufacture of critical system components, assembly of BlueGEN systems, and the quality assurance of individual parts and the overall system. Research, development and testing are done at CFC's own operating facilities in Melbourne, Australia, in co-operation with leading Research & Development institutions.

Figure 4.4: Stack production (source: Ceramic Fuel Cells GmbH)

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Fuel cell systems – single- and two-family houses

Since 2008, political institutions, private companies and research institutions have been backing wide-ranging testing and demonstration of around 550 fuel cell heating systems (output range: 1 kW, low-temperature PEFC and SOFC) for their suitability for everyday service, primarily in single- and two-family residential buildings, in the context of the Callux lighthouse project. A total of 86 million euros is available for the project for a period of seven years. Vaillant GmbH and E.ON New Build & Technology GmbH, both from North Rhine-Westphalia, are participating in this project (Figure 4.5).

Figure 4.5: Vaillant field-testing system for the Germany-wide Callux practical-testing programme (source: Vaillant GmbH)

The Vaillant Group is one of the pioneers in the development of fuel cell heating systems and has been performing successful development in this field for more than ten years. The group's Research & Development activities began as early as 1998. Since 2008, Vaillant has intensified its development activities and concentrated on the most promising technology, Solid Oxide Fuel Cells (SOFC). Five generations of prototypes have been developed since the start of this project. Under the Germany-wide Callux programme of practical trials, Vaillant is testing several prototype generations featuring simple and robust system structures and a start-stop function, which generate 2 kW of heat and 1 kW of electricity simultaneously.

From September 2012 onward, Vaillant has been extending its field-testing and demonstration activities to other countries. Around 130 fuel cell heating systems are being installed and intensively tested across a number of years in single- and two-family houses in other European countries in the context of the ene.field project funded by the Commission of the EU. Further demonstration projects in NRW are also planned, following the implementation of the attractive guideline for the promotion of high-efficiency decentralised CHP systems featuring fuel cells.

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Grouping of fuel cell micro CHP units into a smart network

In the context of a joint virtual fuel cell power plant project Ceramic Fuel Cells (CFC) and Trianel are demonstrating how decentralised fuel cell systems, each with a low individual electrical output, can be grouped together to form a virtual power plant, with this larger unit being remote-controllable via an Internet portal. The idea of grouping decentralised generation units into a smart network, in order to balance out fluctuating feed-in of energy from wind-power and photovoltaics installations, is not new. What is new is the networking of highly innovative fuel cells to form a virtual power plant. In an initial step, twenty-five CFC "BlueGEN" systems (see the article on CFC) are to be grouped together in order to supply power and heat to customer centres and selected municipal-utility customers (Figure 4.6).

The surplus heat from each individual "BlueGEN" unit yielded during operation meets the hot-water needs at the particular location throughout the year. Thanks to the low thermal output of 0.6 kW_{th}, the hot-water supply is assured via continuous operation of the fuel cell, with the result that uninterrupted generation of electricity is also possible during the warmer seasons.

Figure 4.6: Project partners (source: Trianel)

Virtual power plants

The grouping of small decentralised units makes it possible to create large, regulatable generation structures. The electrical output provided can be modulated without any significant loss of the high efficiency achieved (60 per cent at 1.5 kW_{el}, 50 per cent at 1 kW_{el}, < 40 per cent at 0.5 kW_{el}). In addition, output modulation can be accomplished extremely quickly (from 25 to 100 per cent in just 12 minutes). Thanks to this adaptability and its year-round availability, the virtual power plant is the ideal supplementary facility for balancing the fluctuating power generation from renewable energy sources.

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Mobile applications

Intensive work is currently being performed on new energy sources and propulsion systems for road transport, for reasons which include the following:

- Reduction of greenhouse-gas emissions (CO_2, N_2O, CH_4)
- Reduction of dependence on fossil energy sources (oil and natural gas)
- Improvement of air quality (limited emissions: CO, NOx, particulates, CnHm)
- Reduction of noise emissions

Vehicle developers are tackling the following tasks in order to attain these aims:

- Improvement of the efficiency and emission levels of conventional propulsion systems
- Development of new propulsion systems (hybrid propulsion systems, electrical propulsion systems using batteries and/or fuel cells)
- Introduction of new energy sources (natural gas, biofuels, regenerative electricity, hydrogen)

Propulsion systems and energy sources
The majority of activities in this field currently aim at improving conventional internal-combustion-engine propulsion systems based on gasoline, diesel, natural gas and biofuels. Vehicle manufacturers are also increasingly examining the "electrification" of vehicles, in order to meet the demands of the mobility for tomorrow mentioned above (Figure 4.7):

- Hybrid vehicles incorporating an internal-combustion engine, an electric motor and a high-power battery in the vehicle
- Vehicles incorporating an internal-combustion engine and an electric motor, the batteries of which are charged using electricity from the grid (plug-in hybrids and range extenders)
- Purely electrically driven vehicles incorporating batteries charged with electricity from the grid
- Purely electrically driven vehicles incorporating fuel cells, in which hydrogen fuel is converted to electricity

The latter two solution routes will achieve significantly lower specific greenhouse-gas emissions compared to conventional solutions provided they are based on renewably generated hydrogen or electricity, and not on fossil energy sources, i.e., not on hydrogen produced from coal, and not on electricity produced on the current power-mix basis. The "well-to-wheel" analysis of hydrogen/fuel cell propulsion indicates that a significant reduction (30 %) in greenhouse-gas emissions is nonetheless achieved compared to the internal-combustion engine even when hydrogen is generated from natural gas (Figure 4.9).

Hydrogen can be more easily stored than electricity; electricity can be stored, on the other hand, directly from the grid as an energy carrier in the vehicle.

Fuel cell systems as electrochemical energy converters for the generation of electricity for mobile applications are being developed and demonstrated around the globe. Some vehicle manufacturers have stated the post-2015 period for their market launch. It will, nonetheless, firstly be necessary to set up the necessary hydrogen infrastructure.

In parallel, and complementary to this, electric vehicles incorporating batteries are also being developed and offered on the market. Sales have been only moderate up to now, due to short ranges, long charging times and high prices. Despite significant advances in battery technology (Li ion batteries), great leaps in the range of battery-powered vehicles cannot be expected, even in the future. Greater onboard battery capacity automatically means significantly higher vehicle weights. Charging times are also lengthened, and quick "tanking up" becomes impossible. Only a few minutes are needed to fill a hydrogen tank, on the other hand, and ranges of between 400 and 500 kilometres are possible even now.

Both of these vehicle concepts will have a place in future mobility: the battery car more for urban and suburban travel, with the fuel cell car additionally being capable of longer journeys (Figure 4.7).

Figure 4.7: The propulsion-system portfolio for future mobility (source: Daimler AG)

Use of hydrogen in cars

Vehicle manufacturers around the globe are working on the development of electric vehicles incorporating fuel cells. The first small series of fuel cell cars and buses have been completed – by Daimler (Figure 4.8), General Motors, Toyota, Honda and Hyundai, for example – and tested by customers. A number of optimisation tasks remain to be completed prior to a general market launch:

- Longer fuel cell service-life (not less than 5000 h)
- Higher gravimetric and volumetric power density
- Optimisation of catalysts and minimisation of noble-metal input
- Reduction of material and production costs for specific fuel cell system components
- Vehicle integration, including hydrogen storage
- Cost reductions
- Setting-up of the necessary hydrogen infrastructure

The greatest challenges remaining are the still significantly higher costs compared to propulsion-system concepts based on the internal combustion engine, and the creation of the necessary infrastructure. Further advances in materials, system optimisation and series production, with corresponding scale-up effects, will assist in minimising the cost gap.

New propulsion systems for road traffic will achieve major application potentials only if the following two conditions are fulfilled: On the one hand, new propulsion systems should contribute to saving the available energy resources, thus reducing greenhouse-gas emissions, since the efficiency level of these new systems is higher than that of internal-combustion engines. On the other hand, new propulsion systems should permit similar results in terms of road performance, payload, and range levels comparable to the results achieved with conventional propulsion systems. Moreover, the new propulsion systems should allow for a competitive cost-benefit analysis.

Figure 4.8: The Mercedes-Benz B Class F-CELL (80 kW PEM fuel cell, 100 kW electrical propulsion, Li ion battery for 30 kW output, range approx. 400 km, pressurised-hydrogen storage [700 bar], consumption 103 MJ/100 km or 2.9 l diesel equivalent per 100 km) (source: Daimler AG)

Figure 4.9 shows – in line with an analysis from www.optiresource.org – the correlations for conventional propulsion systems using internal combustion engines (ICE) and the corresponding hybrid propulsion systems, also featuring internal combustion engines but with an additional battery (hybrid/ICE) in the cluster at the top centre. All other results for the new energy sources and propulsion systems, as are shown, with examples, in Figure 4.9, can be characterised as follows:

- Electric vehicles featuring a battery and based on renewably generated electricity cause the lowest greenhouse-gas emissions and the lowest specific consumption of primary energy on an overall balance
- Electric vehicles incorporating fuel cells also permit significant reductions in energy consumption and greenhouse-gas emissions
- Depending on the generation of electricity as well as of the hydrogen, both propulsion systems permit a broad bandwidth of balance figures for greenhouse-gas emissions and consumption of primary energy

In the long term, the greatest challenge will be that of providing adequate potentials for the use of renewably generated electricity and hydrogen via an adequate infrastructure and at affordable cost.

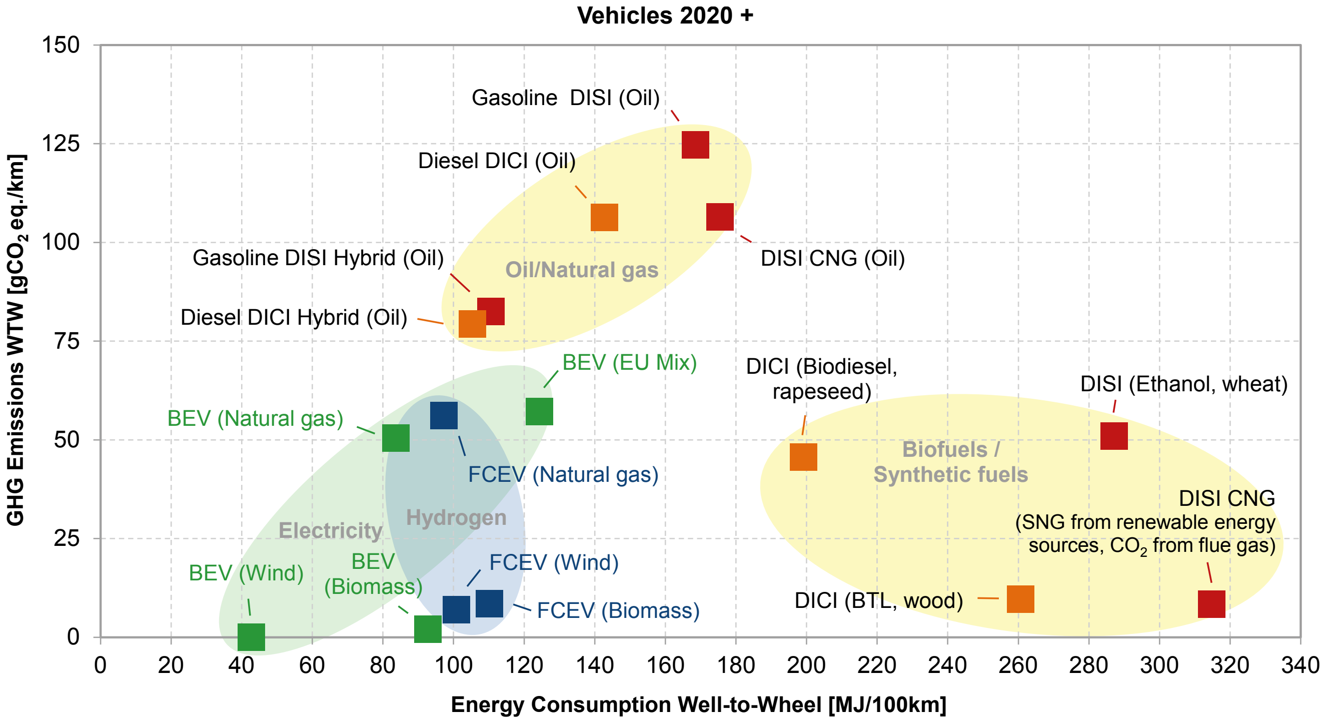

Figure 4.9: Specific emissions and primary-energy consumption for car propulsion systems (available at: www2.daimler.com/sustainability/optiresource/; http://iet.jrc.ec.europa.eu/about-jec/downloads) (source: Daimler AG)

Explanatory notes:
DISI – Direct Injection Spark Ignition
DICI – Direct Injection Compression Ignition
FCEV – Fuel Cell Electric Vehicle
BEV – Battery Electric Vehicle

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Hydrogen-powered buses in NRW

Regional public transport will, in future, play an ever more important role, in view of the ever-increasing flows of traffic. The same requirements for reduction of emissions (exhaust gas and noise) and for climate protection exist here, too, as they do in individual mobility, however.

A significant improvement in energy management, and thus in the operating strategy for the use of fuel cells, is achieved via the "hybridisation" of the fuel cell power train by means of batteries and/or high-capacity capacitors. The fuel cell should be kept in an operating state as constant as possible (which simultaneously extends its service-life), while the electrical storage elements are present to cover peak loads during acceleration. During braking, on the other hand, the electricity generated from the electrical engines will be stored again in the batteries (so-called "recuperation"). This concept achieves considerable cost reductions for fuel cell buses.

One of the first fuel cell/battery/hybrid concepts for bus power trains was implemented by Hydrogenics, of Gladbeck, under the EU HyChain-MINITRANS project (Figure 4.10). The vehicle has a range of around 200 kilometres with a tank filling of six kilograms of hydrogen (the corresponding battery-powered bus achieves a range of only 80 km). This 5.3 m long, 2.1 m wide bus provides seating for twenty-two passengers and reaches a top speed of 33 km/h, with an overall electrical rating of 27 kW. It is thus ideal for use in traffic-calmed inner-city zones. These buses have been in scheduled service with Vestische Straßenbahnen GmbH in the cities of Herten, Gladbeck and Bottrop since May 2009.

Figure 4.10: The fuel cell minibus (source: Hydrogenics GmbH)

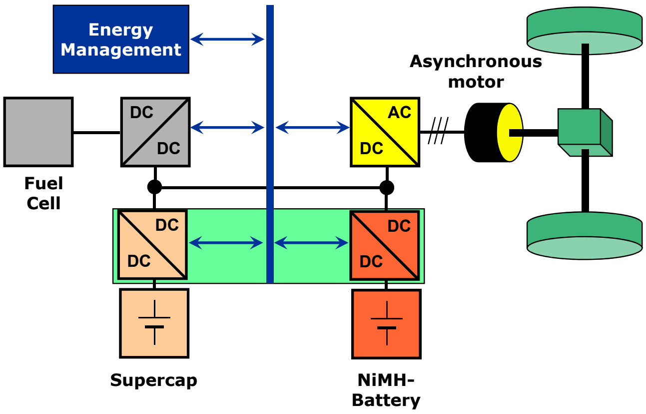

Figure 4.11: The triple-hybrid concept (source: Cologne University of Applied Sciences)

An 18 metre long articulated bus with fuel cell triple hybrid propulsion is being developed for the first time anywhere in the world under a project jointly funded by the state of North Rhine-Westphalia and the Netherlands (Figure 4.11). Together with the batteries and supercapacitors, the fuel cell system generates a total power of 240 kW, making it possible to achieve a top speed of 80 km/h. The bus platform used is the "Phileas", supplied by APTS, of Helmond (Figure 4.12). The 150 kW fuel cell system is from Ballard, of Canada. Vossloh-Kiepe, based in Düsseldorf, is responsible for the energy-management system, while Hoppecke Batterien GmbH, of Brilon, developed the storage module, consisting of NiMH batteries. The RWTH Aachen University Institut für Stromrichtertechnik und Elektrische Antriebe (Institute for Power Electronics and Electrical Drives, ISEA) and the Institut für Automatisierungstechnik (Institute for Automation and Industrial IT) at the Cologne University of Applied Sciences were involved with the development and simulation of the energy-management system, and also of the storage concept. 40 kg of hydrogen are stored in gaseous form in tanks at 350 bar. The bus has a range of around 250 km.

These buses are in service with Regionalverkehr Köln GmbH (RVK) in Hürth, in the Rhine-Erft County, and in the Cologne region, and had already covered more than 50,000 km in scheduled operation by the end of 2013. Consumption is approx. 15 kg hydrogen per 100 km, which is equivalent to 50 l of diesel fuel per 100 km. At an annual mileage of 50,000 km, this achieves a reduction of some 69 tons/a in greenhouse-gas emissions.

Figure 4.12: "Phileas" fuel cell articulated bus operated by Regionalverkehr Köln GmbH (source: RVK)

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BREEZE! – Fuel cell range-extender for battery-powered vehicles

The main challenge in electrical traction is the cost-efficient achievement of long vehicle ranges, coupled with the reduction of electric-vehicle charging times, in order to successfully establish electromobility on the market for the user as an attractive alternative to conventional powertrain concepts.

Fuel cells in vehicle propulsion systems, in combination with battery concepts, permit the achievement of zero-emission long-distance mobility and short fuelling times. The focus of fuel cell range-extender concepts (REX) is on low system and low operating costs. It is possible to dimension the fuel cell in such a way that the vehicle's average power requirement is supplied, even during motorway travel, by the fuel cell alone, thus eliminating time-consuming recharging of the battery system for long-distance operation. Compared to internal-combustion engine alternatives, the REX systems are notable, in particular, for their high efficiencies, low noise and zero emissions.

A 30 kW fuel cell range-extender module is being developed by industrial and research partners in the context of the BREEZE! project funded by the state of North Rhine-Westphalia, with the particular aim of optimising packaging and reducing costs.

The focus at the FEV and the Lehrstuhl für Verbrennungskraftmaschinen (Institute for Combustion Engines) at the RWTH Aachen University is on an innovative endplate concept incorporating highly integrated subsidiary units and sensor systems which will permit optimum integration into a battery-powered sub-compact class vehicle with no sacrifices of passenger or cargo space. The system is to be integrated into the vehicle's spare-wheel recess similarly to combustion engine based range-extender solutions already on the market (Figure 4.13).

Figure 4.13: Experimental vehicle from the FEV Liiona fleet (SmartWheels project) and conceptual packaging of the BREEZE! range-extender module (source: VKA RWTH Aachen)

Gräbener Maschinentechnik, of Netphen, and the Zentrum für BrennstoffzellenTechnik ZBT GmbH (The fuel cell research center ZBT GmbH) Duisburg, are developing and testing the compact stack system, which is based on metal bipolar plates with an active area of more than 300 cm². Liquid cooling, combined with pressurised operation, will permit an extremely compact stack design and the achievement of high power densities. System architecture is to be optimised to meet the requirements of the range-extender function, in order to reduce system costs and complexity.

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Special markets

A further focus in fuel cell applications takes the form of the so-called “special markets”. This term designates uses such as emergency-power supplies, lightweight traction and portable systems, in which the key factor is the replacement of watt- to kilowatt-range batteries in the corresponding conventional applications. The development emphases here are on concepts for reduction of costs, assurance of adequate service-life and the provision of the necessary infrastructure. On early markets, the customer anticipates the following benefits from these “mini” fuel cell applications: longer-term supply of power compared to batteries, high power densities, high efficiencies, compact dimensions, low weight, easy use, environmentally friendly technology, a low-cost alternative, back-up supply, and the elimination of charging times.

In Germany, too, despite the country’s extremely high grid stability, the fuel cell uninterruptable power supply (UPS) is one of the most promising early applications. Fuel cells convince in this field with their longer operating times and their ability to operate across a greater range of temperatures than batteries.

Plant and traffic control systems, and also IT equipment in computing centres, are perceived as entry-level sectors for the commercial use of fuel cell technology. The rapidly growing telecommunications sector is also of great relevance, the focuses being on DSL (broadband) and mobile-telephone stations, digital emergency-services radio and terrestrial trunked radio (TETRA) mobile-radio systems.

UPS in industry

Aluminium Norf GmbH is the world’s largest aluminium remelting and rolling plant, and has been using a Rittal rack-mounted modular fuel cell (FutureE system) in an industrial environment since 2010. As a first stage, the plant fire-brigade of the largest employer in the town of Neuss, complete with the crisis-management centre and the adjoining First Aid station, were provided with assured back-up power. Fuel stocks consist of four 50 litre cylinders of hydrogen, which can be replaced without interruption to operation (Figure 4.14).

Figure 4.14: Fuel cell UPS installation (source: Aluminium Norf GmbH)

This system’s simple structure and the high reliability thus achieved, combined with reduced maintenance and operating costs, were the decisive factors in the selection of this solution.

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Energy off-grid cell phone base stations

E-plus Mobilfunk GmbH & Co. KG is conducting a federally subsidised project for testing energy off-grid cell phone base stations in the active cell phone network. These locations are not connected to the national grid but they generate the necessary electric energy by means of photovoltaics, wind power, fuel cell technology and batteries. High installation costs for connection to the public power-supply grid, and the use of regenerative energy sources, provide the motivation for this concept at each particular location.

The radio equipment technology in operation at these special sites requires a continuous output of between 1.5 and 2.5 kW, depending on circumstances at the location. All locations use a combination of a photovoltaic (PV) installation on a two-axis tracker system, a vertical-axis wind-power turbine (WPI) on a spun concrete mast, fuel cell technology employing hydrogen as the energy source, and buffer batteries (Figure 4.15).

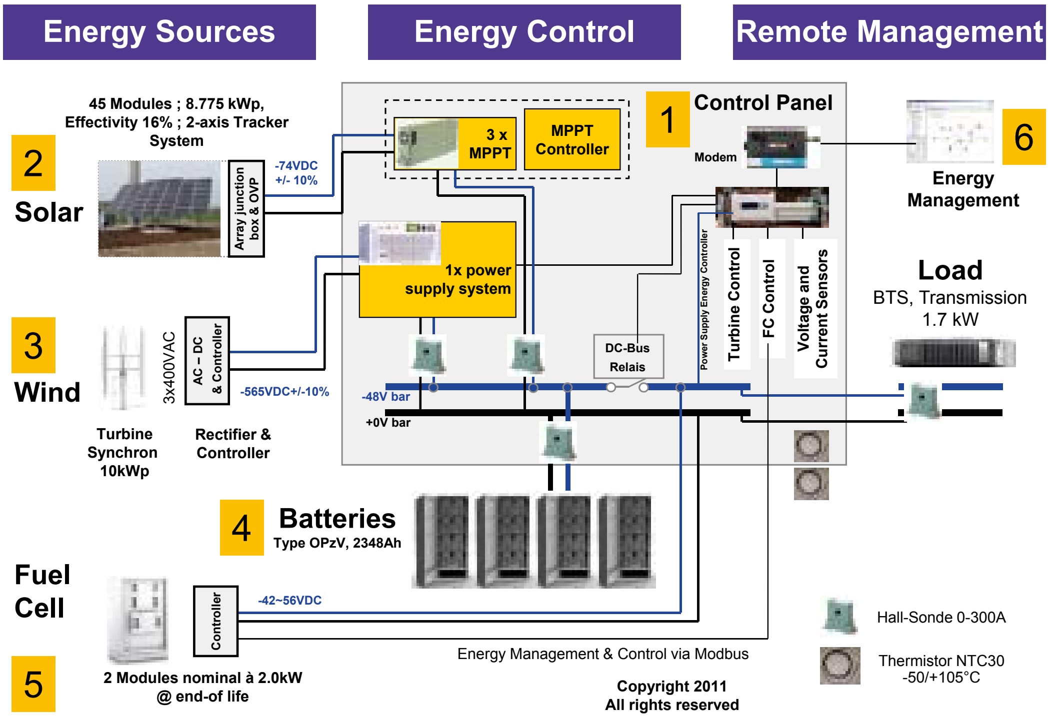

Figure 4.15: The combination and manner of operation of the energy sources at the Versmold location

The PV installation has an output ranging between 8.27 and 10.02 kWp and is the main energy supplier. The WPI generates 10 kWp or 6 kWp, depending on the model selected, and contributes up to a maximum of one third of energy needs, depending on the region. The fuel cells are installed redundant, generate 2.5 kWp each, and can, assuming undepleted stocks of hydrogen (two batteries, filling pressure 300 bar), supply the radio equipment with energy sufficient for up to twelve days of operation if the other systems should fail. The batteries provide buffer capacity. It is thus possible to feed a constant 48 V DC voltage and to build up simultaneously an additional reserve for up to two days of operation (assuming 100 % SOC).

The radio equipment, the energy control and management system, the fuel cells and the fuel storage equipment are housed in a cabin (10’ or 20’). The space requirement for the complete station is around 250 m², twice as much as is needed for conventional stations.

Two locations are currently operational: Versmold, since May 2011, and Büren (near Brilon), since December 2012. A further station, at Waldfeucht (County of Heinsberg) has received approval and was integrated into the network in the spring of 2014, while a fourth location has also received approval and will be built in the summer of 2014 also near Waldfeucht. There have, up to now, been no serious operating difficulties, with the exception of expected start-up problems caused by these systems’ complexity.

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5 Hydrogen and fuel cell activities in the state of North Rhine-Westphalia

With the setting-up of the Fuel Cell and Hydrogen Network NRW in 2000, the state government of North Rhine-Westphalia created an instrument aimed at accelerating the development of fuel cell technology in this state. The Network's activities are backed up by carefully targeted project funding, primarily under the auspices of the "progres.nrw – Innovation" programme. The state government and the European Union (European Regional Development Fund, or ERDF) have since provided some 110 million euros for around one hundred hydrogen and fuel cell projects. The total investment volume amounts to a good 185 million euros, while the range of topics covered in these projects (Figure 5.1) extends from the evolution of individual system components such as compressors and sensors, up to and including the development and testing of complex portable, stationary and mobile fuel cell applications. The following may be mentioned as particularly outstanding projects:

- The development of an 18 m articulated bus featuring hybrid fuel cell propulsion
- The construction of the Düsseldorf hydrogen filling station for fuel cell cars
- The setting-up of Anwenderzentrum h2herten GmbH (h2herten application centre)
- The operation of fuel cell minibuses at Vestische Straßenbahnen GmbH
- The development of quick-acting hydrogen valves for pressures of 700 bar
- Hydroforming processes for the production of metal bipolar plates
- The development of a fuel-cell-based range extender for battery-powered vehicles
- Wind-power electrolysis in Herten

NRW Hydrogen HyWay

The "NRW Hydrogen HyWay" lead project provides the strategic framework for the various activities in the field of fuel cell and hydrogen technology. The programme covers five topic focuses:

- Conversion and storage of surplus regenerative electricity in the form of hydrogen, including subsequent use in the energy system
- Infrastructures for the introduction of renewably generated hydrogen as an innovative vehicle fuel (production, storage and fuelling technology for the focal applications of regional/local public transport and car fleets)
- Testing of vehicles incorporating fuel cell technology (with the emphasis on regional/local public transport, utility vehicles, plus special applications supplementing in-car use funded by the Federal Government/the EU)
- Research, development and testing of decentralised fuel-cell-based combined heat and power (CHP) cogeneration, virtual power plants, with the main emphasis on fuel cell CHP units and hybrid power plants
- Research & Development into technological optimisation and cost reductions, pre-commercial testing of new developments in larger-scale field tests

Against the background of the important paths currently being set for the market launch of hydrogen (as an energy storage medium, for instance) and fuel cell technology (including micro CHP units and mobility), the new state government has publicly committed itself to hydrogen and fuel cell technology via "NRW Hydrogen HyWay". In initiating this unique strategic programme in the field of hydrogen and fuel cells, North Rhine-Westphalia is playing a pioneering role throughout Germany, and enjoys correspondingly high regard at both national and international level.

Figure 5.1: Hydrogen activities in North Rhine-Westphalia

Regional activities

Hydrogen Region Rhineland

Hydrogen is produced in large quantities in the Cologne region as a byproduct of the local chemical industry (primarily in chlorine production and oil refining). Along with other projects, the Network HyCologne Hydrogen Region Rhineland, in co-operation with public and industrial partners, organises the supply of this industrial hydrogen as a source of energy for transport. The now more than three-year operational phase (start: 2011) of the appurtenant filling station and buses impressively demonstrates this system's technical and organisational feasibility, and also the high level of determination and financial commitment on the part of the participating partners.

The first application saw the introduction of two "Phileas" hybrid fuel cell buses to everyday service from 2010 onward. These buses run in Hürth, in the Rhine-Erft District and in the Cologne region itself, and had already covered more than 50,000 km in scheduled operation by the end of 2013.

For a period of three years (2009 to 2012), "Chemergy – Supply of Byproduct Hydrogen for Transport Projects" pursued, within the framework of the National Innovation Programme (NIP), the aim of achieving public access to the previously closed chemical industry infrastructure in order that hydrogen could be used as a source of energy for mobility and transport. Since the end of the funding period, this filling station, constructed by Air Products, has successfully continued in operation under the management of the Hürth and Brühl municipal utilities, and has been notable for its extremely high availability (> 98 %).

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The h2-netzwerk-ruhr (h2-network-ruhr) is an alliance of municipalities and other public institutions, enterprises, associations and private persons. The towns participating up to now include Marl, Bottrop, Gladbeck and Herten. The alliance pursues the aim of shaping boundary conditions in the Ruhr metropolis in such a way as to establish this region as a location of Europe-wide importance for the hydrogen and fuel cell industry. The focus is on the co-ordination of the region's range of projects, and also on PR and educational activities.

Under the "Kommunale Entwicklungsschwerpunkte Ruhr" initiative ("Municipal development focuses Ruhr"), the City of Herten is expanding existing fuel cell and hydrogen activities on the site of the former Ewald coalmine into an internationally leading capability centre (Project: Anwenderzentrum h2herten GmbH (h2herten application centre)). The aim of this project is the long-term and sustainable creation of future-orientated jobs in the fuel cell and hydrogen sector.

The centre, opened in the autumn of 2009, provides a range of fuel cell technology enterprises with around 1800 m^2 of office and 1200 m^2 of technology-centre space (Figure 5.2).

Figure 5.2: The h2herten Hydrogen Competence Centre

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International activities

HyER

“HyER” stands for “Hydrogen, Fuel Cells and Electromobility in European Regions” and was founded at the initiative of the European Commission in 2008 (Figure 5.3). This partnership currently co-ordinates the European activities of thirty-seven European regions and cities in the context of European initiatives and programmes. It promotes the dissemination and commercialisation of hydrogen and fuel cell technology (stationary and mobile applications) and of electromobility (both battery- and fuel-cell-based), in addition to the development of the necessary infrastructures. It functions in parallel as a point of contact on EU projects and provides support in the submission of project applications. HyER’s three core activities are:

- The drafting and distribution of recommendations for action for decision-makers within the member municipalities and regions on the basis of up-to-date technical information (HyER is involved in a large number of EU projects)
- Analysing, evaluating and, where appropriate, also contributing to, the shaping of a European promotion and funding framework for municipalities and regions for the development, testing and market launch of innovative technologies
- The compilation and elaboration of robust development scenarios for innovative technologies within the member regions and municipalities, combined with the analysis and evaluation of the respective backers and motivations

The European Electromobility Observatory (EEO), which compiles and evaluates the results of all European electromobility projects, was created by the Commission in late 2012 in response to a HyER initiative (Figure 5.3). This database has the aim, inter alia, of creating a “fact bank” for the shaping of future European political provisions, such as codes, guidelines and promotion programmes, for example.

North Rhine-Westphalia is a founding member of HyER. The current Executive Director is Dr. Andreas Ziolek, of ee energy engineers GmbH, one of EnergyAgency.NRW’s sponsor companies.

Figure 5.3: HyER partner regions

Co-operation with non-European regions

Outside Europe, the Fuel Cell and Hydrogen Network NRW has for many years conducted co-operation with the Canadian Province of British Columbia and the Japanese prefecture of Fukuoka. Both regions have gained reputations in their respective countries for their out-of-the-ordinary commitment to hydrogen and fuel cell technology.

As long ago as 2004, the Network signed a memorandum of understanding on “Collaboration on Fuel Cell Development and the Support of the Hydrogen Economy” with its Canadian counterpart, Fuel Cells Canada. Like NRW, Fukuoka has a comprehensive strategy for the establishment of a hydrogen infrastructure and for the dissemination of fuel cell technology, and is thus the Japanese leader for the market launch of this technology. An institution comparable to the CEP exists in Japan, in the form of the “Research Association for Hydrogen Supply/Utilization Technology (HySUT)”, and is tackling the task of setting up the necessary hydrogen infrastructure. Numerous related projects have already been initiated in the Fukuoka prefecture.

Intensive interchange and benchmarking on infrastructural concepts, political boundary conditions and technical standards are conducted with both of these regions. Numerous delegations have also visited fuel cell projects in NRW.

Further information and contacts:
www.hyer.eu
www.chfca.ca
www.hysut.or.jp/en/index.html

Fuel Cell and Hydrogen Network NRW

The aim of the Fuel Cell and Hydrogen Network North Rhine-Westphalia, founded in 2000, is the establishment of hydrogen and fuel cell technology as a permanent element in future energy supply systems, and the simultaneous exhaustive exploitation of the economic potentials of this technology for NRW as an industrial location. The challenges of the energy turnaround, climate protection, the boosting of energy-efficiency, and the expansion of renewable energy sources, make hydrogen and fuel cells key technologies in all sectors of the future energy and transport system.

Even now, more than four hundred representatives of industry and science are actively co-operating and utilising the numerous services provided by this network. Around 70 per cent are industrial partners (small and medium-sized enterprises, in the main), while 20 per cent are representatives of research institutions and 10 per cent originate from other sectors. These players are based predominantly in North Rhine-Westphalia, although other federal states and other countries are also represented. The network has its offices in Düsseldorf, and is the largest of its type in Europe.

The principal focus of the network's activities is on the initiation of co-operation projects, with the main emphasis of project work increasingly shifting from research and development toward testing and market preparation. The network is available to its members as a contact for the more specific definition of project concepts, the identification of suitable funding programmes and as a channel of communication with the political world. The network members are also intensively involved in both German and European promotion activities.

The network created the "Hydrogen" and "Fuel Cell" platforms in order to facilitate technical interchange and communications between its members. The latter also meet at regular intervals in special expert groups covering topics such as the "H_2 System" and "Power-to-Gas", in order to discuss specific questions in minute detail.

In the interest of promoting young scientists, the network has for several years now also organised the "Fuel Cell Box NRW" school-pupils' competition (Figures 5.4 and 5.5), in which around two hundred teams from throughout North Rhine-Westphalia regularly participate.

In the public relations field, the network enables its members to be represented on joint stands at international trade fairs and exhibitions, such as the FC Expo, in Tokyo, and the Hannover Messe trade fair.

Figures 5.4 and 5.5: Prize winners of the "Fuel Cell Box NRW" school-pupils' competition (www.fuelcellbox-nrw.de)

The network has contributed to NRW nowadays being regarded, both nationally and internationally, as one of Europe's leading fuel cell locations. This fact is illustrated, inter alia, by the state's presidency of the European Hydrogen, Fuel Cells and Electromobility in European Regions (HyER) partnership, and the attraction to the state of important fuel cell and hydrogen technology enterprises, such as Ballard, Hydrogenics and Dynetek, of Canada, along with Ceramic Fuel Cells, based in Australia. Japanese companies are also already co-operating on Research & Development, and on the production of individual fuel cell components, with partner companies and institutions in NRW.

Companies and institutions which have up to now not been directly involved in the field of fuel cell, battery and/

or hydrogen technology but which, thanks to their know-how, could make useful contributions both to the development of fuel cell and battery systems, and also of corresponding components, and to the topic of the production (e.g. electrolysis), storage and transmission of hydrogen are expressly encouraged to join this network.

On the road to the market launch, which is now coming ever more clearly into focus, it is of pivotal importance to also increasingly include new players from outside the "hydrogen and fuel cell scene", such as energy suppliers, wind-farm operators, grid operators, transport undertakings, fleet operators and new industrial partners (Figure 5.6).

Membership of the network is free.

Figure 5.6: Fuel cell buses at Regionalverkehr Köln GmbH (source: Regionalverkehr Köln GmbH)

Fuel Cell
and Hydrogen
Network NRW

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6 Explanatory Notes

EnergieAgentur.NRW (EnergyAgency.NRW)

EnergyAgency.NRW works on behalf of the state government of North Rhine-Westphalia as an operational platform with broad responsibilities in the field of energy, ranging from energy research, technological development, demonstration and market launches, via energy consulting, up to and including occupational further training. In times of high energy prices, it is now more important than ever to accelerate the evolution of innovative energy technologies in NRW and to demonstrate impartially how companies, municipalities and private households can economise on energy consumption and use renewable energy rationally.

EnergyAgency.NRW ’s activities comprise, in detail:

Cluster management
On behalf of the NRW Environment and Climate Protection Ministry, EnergyAgency.NRW is operating the powerful cluster “EnergyRegion.NRW” for climate protection incorporating the eight networks for Biomass, Fuel Cell and Hydrogen, Energy-Efficient and Solar Construction, Geothermal Energy, Fuels and Drives of the Future, Power Plant Technology, Photovoltaics, and Wind Energy. The focus: highly competitive co-operation ventures, with the aim of initiating innovative projects and products, accelerating their evolution to market maturity, and exhaustively exploiting all economic potentials. The mandate also includes support for companies from NRW in foreign-trade activities.

Also part of EnergyAgency.NRW’s responsibilities is the Cluster EnergieForschung.NRW (EnergyResearch.NRW – CEF.NRW), on behalf of the NRW Science Ministry, in this case. CEF.NRW sees itself as the contact source on all matters concerning energy research in NRW, and is responsible for furthering co-ordinated co-operation between research, science and industry.

Energy consulting
In this field, EnergyAgency.NRW engineers provide information on energy weak points, ranging from building automation systems up to and including companies’ production operations. The spectrum covered extends from the heating system, via heat recovery, up to insulation for protection against heat and cold in large industrial buildings, and from leak detection up to the drafting of energy concepts. The engineers advise on sources of funding, assist companies in reducing energy costs, and thus also contribute to enhancing commercial competitiveness.

Further training
EnergyAgency.NRW organises a whole series of further-training seminars, including events for end consumers. Further-training institutions, energy-supply utilities, associations, clubs, universities, municipalities and companies in NRW are all entitled to make use of the range of fifty different seminars. User-motivation projects, such as the “aktion.Efit” and “mission E” campaigns for company workforces, are also available under this programme. EnergyAgency.NRW also operates an on-line Internet platform for basic and further occupational training in the form of the “Knowledge Portal Energy”.

EnergieDialog.NRW (EnergyDialogue.NRW)
The “EnergyDialogue.NRW” information and advice platform on renewable energy in NRW is an active mediating and advisory interface provided for citizens, municipalities and investors by EnergyAgency.NRW on behalf of the NRW Climate Ministry. EnergyDialogue.NRW is intended to make an active contribution to the resolution of conflict situations. Professionally supervised mediation services are available to participants in North Rhine-Westphalia should such conflicts occur – in the context of planning and approval procedures, for example.

Joint campaigns
State-wide campaigns and joint projects, such as “NRW Saves Energy”, “AltBauNeu”, “50 Solar Estates in NRW”, “100 Climate Protection Estates in NRW”, “Photovoltaics NRW”, the “Wood Pellets” campaign and “Heat Pump Market Place NRW” provide information in NRW on environmentally friendly and innovative heating technologies, along with tips on saving energy.

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Cluster EnergieRegion.NRW (EnergyRegion.NRW)

Energy and industry in North Rhine-Westphalia
North Rhine-Westphalia has a long tradition as an energy region. The supply and use of energy have exerted a decisive influence on economic and social development here since the dawn of the industrial age.

The region's panoply of global industrial players, medium-sized enterprises and research institutions make North Rhine-Westphalia a location with a unique concentration of capabilities in future energy-industry solutions. Around 1.5 million people are employed in energy-intensive sectors in this state.

On increasingly globalised dynamic and mobile markets, however, the classical proximity of industry, science and government is frequently not enough. Potentials for innovation can, instead, be exploited, above all, by more intense networking of the persons involved in clusters sited along – in some cases multi- or cross-sector – value chains.

EnergyRegion.NRW stands for innovation, tradition, impartiality and receptiveness to new technology. It groups together 3300 companies and institutions in the energy industry. Three quarters of the companies are small and medium-sized enterprises (SMEs). The Cluster also includes sixty-four universities, 107 institutes and ninety-four associations; 5200 specialists contribute to its various workgroups and networks. EnergyRegion.NRW supplies 30,000 media channels and decision-makers with information and data.

The Cluster's activities therefore focus on the acceleration of innovation processes and on the optimised market launch of innovative products.

EnergyRegion.NRW combines eight networks, covering the following topics:

- Power Plant Technology
- Fuel Cell and Hydrogen
- Biomass
- Energy-Efficient and Solar Construction
- Fuels and Drives of the Future
- Photovoltaics
- Geothermal Energy
- Wind Power

The Cluster EnergyRegion.NRW's activities are aimed at a range of different players:

Research & Development
R&D institutions must network more intensively with energy-industry companies in North Rhine-Westphalia, in order to evolve practically and application-orientated solutions for the energy and climate-protection challenges of tomorrow. EnergyRegion.NRW provides a platform for this.

Small and medium-sized enterprises (SMEs)
EnergyRegion.NRW enables SMEs to network reliably, technologically receptively and without narrow industrial interests in the Energy Economy cluster. Among other services available, EnergyRegion.NRW also provides SMEs in North Rhine-Westphalia with cross-company projects, introductions to potential partners, impartial first-hand information, and access to political institutions.

Large companies
For major companies, intensive use of the structures provided by EnergyRegion.NRW, and networking with partners in the energy industry in North Rhine-Westphalia, generates significant advantages over their international competitors. In EnergyRegion.NRW, large companies benefit from co-operation with network partners for the identification of smaller but innovative enterprises, the expansion of their range of products and services, and for the regionalisation of their own capabilities.

Figure A-1: Solar tower in Jülich (source: DLR)

Political decision-makers
North Rhine-Westphalia as a location benefits to a remarkable extent from the relaying of transparent and up-to-date information from authorities and political decision-makers to industrial enterprises.

EnergyRegion.NRW's cluster management and networks assure frank and open interchange with the relevant bodies and individuals, thus making the cluster an interface between NRW's energy industry and its people. The municipalities draw benefit from EnergyRegion.NRW thanks among other things, to the strengthening of the region's economic structure, the commitment of top-performing enterprises and therefore from the upgrading of their location.

Unity of management
The management of the EnergyRegion.NRW is in the hands of the EnergyAgency.NRW. The cluster managers and a team of eight network managers are competent and experienced contact persons acting for players in the EnergyRegion.NRW, with other partners at home and abroad. The networks' partners are supported by the cluster management from the initial idea to market launch in projects which are cross-company and possibly accompanied by research institutions. In addition the cluster management ensures close consultation with the energy research cluster.

Figure A-2: Wind turbine
(source: EnergieAgentur.NRW)

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Cluster EnergieForschung.NRW (EnergyResearch.NRW)

The Cluster EnergyResearch.NRW (CEF.NRW) works on behalf of the Ministry of Innovation, Science, Research and Technology of the German Federal State of North Rhine-Westphalia on the implementation of the state government's energy-industry and climate-policy targets in the field of energy research.

CEF.NRW focuses its interdisciplinary and transdisciplinary activities on the complex energy-supply system as a whole. The electricity, heat and gas supply systems, along with the corresponding storage technologies, are the perceived sphere of activity, on the basis of the primary-energy conversion processes in the renewable and fossil energy sector so vital for the energy turnaround. Special attention is devoted to the processes of conversion between the various secondary energy sources, such as "power to gas", for example, which all relevant studies highlight for their increasing importance.

In addition to purely technological transformation, the energy turnaround also presents a new form of challenge with respect to the organisation of the process of public participation. Scientific support and the evolution of specific solution strategies are required here. The cluster also perceives a need for action in this field.

One of CEF.NRW's aims is to achieve more rapid practical application of advances in technological and socio-economic knowledge. The cluster initiates research & development projects in co-ordinated co-operation between research institutions and industry specifically for this purpose.

CEF.NRW also functions as a transfer channel between the energy-related activities of the EU and the federal government, on the one hand, and social initiatives, on the other.

Like EnergyRegion.NRW, CEF.NRW is managed and organised by EnergyAgency.NRW.

CEF.NRW
Cluster EnergieForschung

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Figure A-3: Fuel cell test system at the DLR (source: DLR)

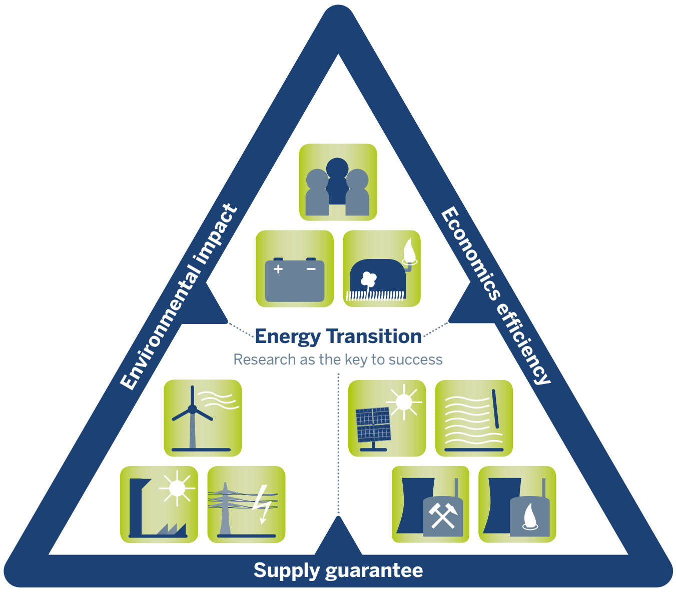

Figure A-4: Energy research in North Rhine-Westphalia – the key to the energy turnaround (source: Wiedemeier Kommunikation)

The properties of H_2 at a glance

Hydrogen is the “lightest” of all gases, and has a density of 0.0899 kilogram per standard cubic metre (standard temperature and pressure). It was first discovered by H. Cavendish in 1766. J. Dalton selected the mass of the hydrogen atom as the basis for the system of chemical atomic weights in 1808 (applicable until 1899). The hydrogen atom is the first in the periodic table, with the atomic number 1. The earth’s atmosphere contains only traces of hydrogen, but this element is otherwise very widely present, in fixed state in water and organic compounds. Hydrogen makes up around 1 per cent of the earth’s crust. The boiling point of hydrogen is -253 °C.

Of all energy sources, hydrogen has the highest mass-specific but also the lowest volume-specific energy density, a fact which, depending on the particular application, can have diverse implications for selection of the most suitable mode of storage (Table A-1).

Hydrogen is characterised by the following properties:

- Non-toxic, non-corrosive
- Non-radioactive
- Non-water-polluting
- Non-carcinogenic
- Lighter than air
- Rapidly dissipated (diluted) in air

There are, in addition, a number of safety aspects which must be borne in mind: not visible during combustion, broad ignition limits in air, and easily ignitable (low ignition energy), high combustion rate, tendency to cause problems with materials (embrittlement, low temperatures).

Comparison of physical data of energy sources

Properties		**Hydrogen**	**Methane**	**Gasoline**
Lower Heating Value	kWh/kg	33	13,9	12
	MJ/kg	120	50	43
Density (15 °C, 1 bar)	kg/m³	0.09	0.72	748
Ignition range in air	% vol.	4-75	5-15	1-8
Minimum ignition energy	mWs	0.02	0.29	0.24
Combustion rate in air ($\lambda = 1$)	cm/s	265	43	40
Diffusion coefficient in air	cm²/s	0.61	0.16	0.05
Toxicity		non-toxic	non-toxic	Crude benzol TRC* 1 ppm
Specific CO_2 emissions	g/MJ	0	58	74

* TRC = Technical Reference Concentration

Source: after Biedermann et al. (2006)

Table A-1: Comparison of physical data of energy sources

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