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Hydrogen Strategy Group
of the
Federal Ministry of Economics and Labour

Strategy Report on Research Needs in the Field of Hydrogen Energy Technology

Munich, Germany,
January 2005

Declaration of Exclusion

This report was prepared on behalf of the Federal Ministry of Economics and Labour (BMWA) by the Research Institute for Energy Economy (Forschungsstelle für Energiewirtschaft e. V.) in cooperation with the members of the BMWA Hydrogen Strategy Group and financed by Project Management Jülich (PtJ) of BMWA within the framework of the ET 6903 M project. It will contribute to the factual discussion of issues of hydrogen research and hydrogen technology development. The authors are responsible for the contents of the report. The report does not necessarily reflect the view of BMWA or PtJ nor can any responsibility of or claims on BMWA or PtJ be derived from this report.

Preface of BMWA

The Federal Government has intensively supported the research and development work on hydrogen technologies for the energy market over the past 30 years. In this process, excellent and internationally pioneering technological results have been achieved and valuable insights acquired for future development efforts. German industry and research are among the world's leaders in both the "regenerative" and the "conventional" industrial production and processing of hydrogen. This is also true for the technologies used for hydrogen utilization, especially in vehicles and fuel cells. Despite all success it is uncontested that an additional considerable R&D effort is needed to make use of the opportunities offered by the hydrogen technologies for the energy economy, above all in view of economical and ecological aspects.

The political interest for a future hydrogen economy is high in the European Union and worldwide. At the end of 2003 the International Partnership for the Hydrogen Economy (IPHE) was established and early 2004 the European Hydrogen and Fuel Cell Technology Platform, both having the aim of cross-border cooperation on research and development (R&D) extending as far as the market introduction. The Federal Ministry of Economics and Labour (BMWA) and German specialists have important positions on bodies involved in European and international cooperation.

To facilitate this goal we convened at an early stage a national "Hydrogen Strategy Group," composed of experts from industry and science as well as representatives of the relevant federal and state ministries, in order to strengthen national and international R&D cooperation. It has compiled the accompanying comprehensive report on research needs in the field of hydrogen energy technologies. The report is a valuable contribution to the national discussion of the sustainable approach toward a possible hydrogen energy economy and toward preparing the way to cooperative ventures in Europe and beyond.

I sincerely thank all of those involved for their intensive collaboration. They have created a sound foundation for the common tasks ahead. I welcome the proposal to develop a hydrogen strategy for Germany. On one hand, it is important to minimize financial and R&D risks in view of the many still unresolved development problems that have been named. On the other hand, the key question of the economic and environmentally friendly production of hydrogen must be resolved in a very concrete manner. This includes the investigation of the idea to produce hydrogen in the future by offshore wind energy as against other production processes. The electricity from zero-emission coal and gas power plants could thus also become viable for environmentally friendly hydrogen production in the longer term; BMWA is funding the development of such power plant technologies (R&D concept COORETEC).

Moreover, I am looking for the strategy discussions in order to clearly define public and industrial interests in national, European, and international cooperation.

Georg Wilhelm Adamowitsch
State Secretary
Federal Ministry of Economics and Labour

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Summary

Under the leadership of the Federal Ministry of Economics and Labour and in cooperation with the Federal Ministry of Transport, Building and Housing and the Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, the Hydrogen Strategy Group was instituted with the aim of defining a common goal for the national activities in the field of hydrogen technology and strengthening the German position and presence in international cooperations. The motivation for the commitment of all those involved and the driving force for the use of hydrogen in the energy sector are the following aspects:

Hydrogen – Energy Carrier of the Future

Hydrogen and the security of energy supply
Hydrogen can be produced from all (fossil, nuclear and renewable) sources of primary energy. This enables a more flexible adaptation of the energy mix to the situation of global resources.

Hydrogen as a bridging technology
The transition phase to an energy economy based on hydrogen produced from renewable sources can be realized by fossil energy carriers and eventually CO_2 disposal. In this case, hydrogen produced from conventional energy carriers can also provide efficiency advantages.

Hydrogen and renewable energies
Hydrogen enables an enhanced integration of renewable energies into the future energy infrastructure. Hydrogen thus provides a contribution towards conserving depletable resources.

Hydrogen and climate protection
Hydrogen technologies can reduce CO_2 emissions while providing the same energy services. Moreover, the use of hydrogen is nearly emission-free at the users.

Hydrogen and fuel cells
Hydrogen technology and fuel cells provide economic and ecological advantages independent of each other and can be combined to obtain particularly energy-efficient solutions.

Hydrogen and competitiveness
Innovative hydrogen technologies open up globally new markets – technological leadership enhances the economic power and creates new jobs in German enterprises.

Hydrogen in Germany
Germany's strength is the scientific and industrial know-how for the development and production of hydrogen and fuel cell technologies. These competences are the basis for a pioneering role in intensive market preparation.

Hydrogen technology will thus play a significant part in a future energy economy. From the Strategy Group's point of view, there is a need for action in the following fields to attain technological leadership together with the European partners:

Need for action to attain H_2 technology leadership

The research and development activities to increase competitiveness must be considerably intensified:

- improvement of hydrogen production processes, hydrogen storage and hydrogen infrastructure
- advancement of application technologies such as fuel cells and internal combustion engines
- cost reductions along the value-adding chain
- accompanying systems analysis and holistic assessment, e.g. for an efficient priority setting of R&D activities

Initiative and lighthouse projects with the following goals must be implemented for market preparation:

- increasing the commitment by sharing the risks
- demonstrating technical feasibility
- evaluating practical experience
- increasing the acceptance in society by objective information dissemination
- enhancing national, European and international cooperation
- building up nuclei for a future hydrogen energy economy

Creation of reliable boundary conditions for developers, producers and investors:

- definition of national targets and of a European roadmap
- rapid coordination and application of international regulations and laws
- binding statements on market introduction tools

In order to maintain the actors in research, development and industry for hydrogen technology and know-how in Germany and to attract new actors, long-term and continuing policy support in the above areas is required from the Federal and state governments. This report serves to summarize the Federal Government's past funding policy in the field of hydrogen and fuel cell technology.

Munich, 31st of January, 2005

Preface

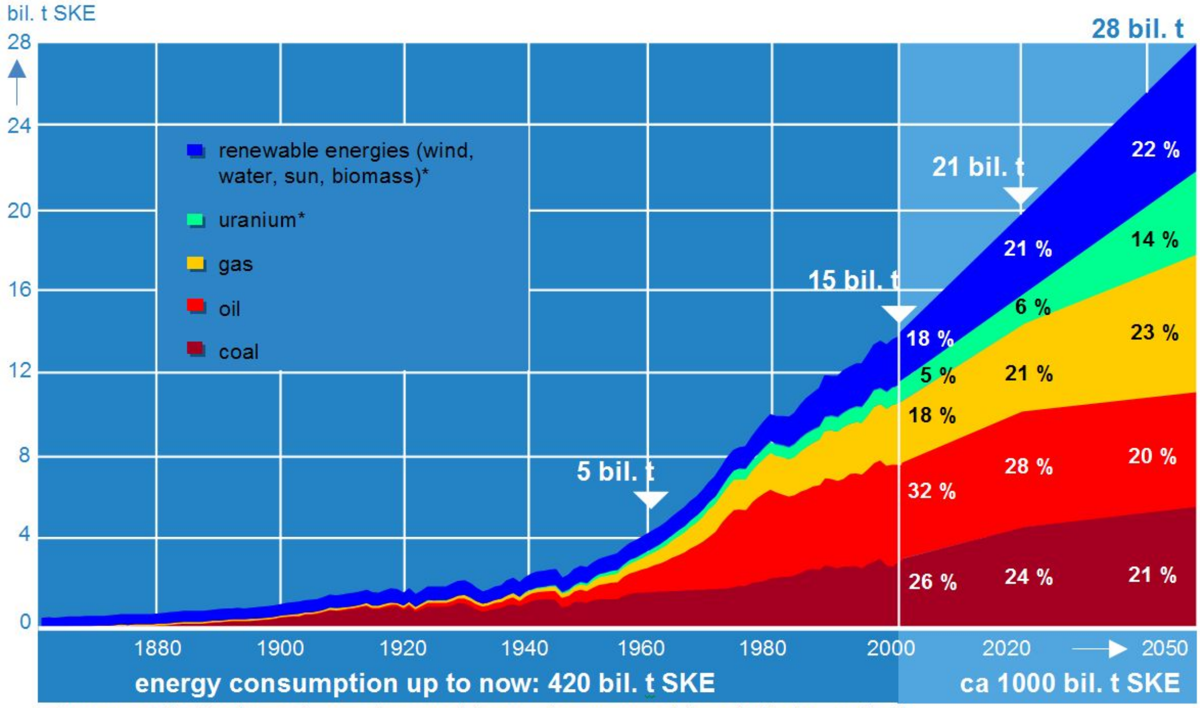
In the year 2003, global activities for a future hydrogen energy economy received new impetus. The creation of the "European Hydrogen and Fuel Cell Technology Platform" and the foundation of the "International Partnership for the Hydrogen Economy" should be particularly mentioned here. The Hydrogen Strategy Group of the Federal Ministry of Economics and Labour was instituted in 2003 in cooperation with the above-mentioned ministries with the aim of defining a common goal for the national activities in the field of hydrogen technology and strengthening the German position and presence in international cooperations.

The members of the Strategy Group represent nearly the entire German hydrogen community composed of industry, research and initiatives as well as state and federal ministries. Numerous experts from the fields of hydrogen production, logistics and application have contributed their know-how and supported the Strategy Group.

This strategy paper is the result of the joint work by the members of the Strategy Group. It describes the political boundary conditions, the state of the art of hydrogen technology and the further development efforts required for a market penetration of this technology. On this basis, recommendations were formulated by the Strategy Group to help politicians and decision-makers promote the research and development of hydrogen energy technology in Germany in a targeted manner and thus create the basis for the introduction and integration of this important component of a future sustainable energy economy.

1 Energy economy and political boundary conditions

The global demand for energy will dramatically rise in the coming decades. According to predictions by the World Energy Council, an average growth rate of about 1.3 % per year is expected for global energy consumption up to the year 2050 assuming a business-as-usual scenario.



*power production by nuclear and renewable energies assessed by substitution method

source: WEC, IIASA, IEA/OECD 2001/2002

Figure 1-1: Development of global energy consumption

Such an increase in energy consumption in this period can only be appropriately covered by fossil and nuclear energy carriers despite the growing share of renewable energies. The associated rise in CO_2 emissions and other types of environmental pollution, but above all the increasing shortage of fossil energy carriers, makes the search for suitable alternatives for energy supply indispensable.

The security of supply is of decisive significance. Fossil energy carriers, especially oil and natural gas, only occur in sufficient quantities in a few regions of the world. Access to these resources depends on the respective technical and economic conditions and is characterized by political and ecological factors and associated with geopolitical risks. These factors increasingly lead to volatile and often high price trends, on the one hand, while political measures require the enhanced reduction of greenhouse gas emissions and other environmental pollution, on the other hand.

Today's less developed regions will contribute more than half of the global CO_2 emissions by 2030 due to their enhanced economic development and will increase the pressure on the energy markets. The availability of efficient technologies is therefore also required for these groups of countries. For reasons of climate policy and from the aspects of industrial policy, increased efforts in technological development aiming at new environmentally compatible energy systems must therefore be made above all by the industrialized countries.

A coherent strategy is required covering both energy production and energy demand in an overall approach, i.e. fuel procurement, transport, distribution, energy conversion up to the role of energy technology and the end users. In the short and medium term, such a strategy must necessarily aim at increasing the energy efficiency and at an increased use of renewable sources of energy. In the long term, a hydrogen-based supply – complementing electricity – can make an essential contribution to energy supply. The technological advancement of hydrogen-based systems for mobile applications, in the energy sector, in industrial applications and for households opens up the possibility for an efficient and environmentally benign energy supply alternative.

Research, development and the testing of new technologies in experimental and demonstration projects is of central significance for entry into a hydrogen-based supply system. In this document, the different fields of activity with their development options will be described and assessed. The recommendations derived are intended to help politicians decide where and to what extent and with what time horizon the future course in research funding should be set, in order to develop innovative products and marketable applications on a medium-term basis.

1.1 Why hydrogen?

Hydrogen is not a primary energy source like coal, gas or oil, but a secondary energy carrier as is electricity. It can be produced in various ways, by energy systems based on conventional technologies as well as from renewable energy carriers (cf. Figure 1-2).

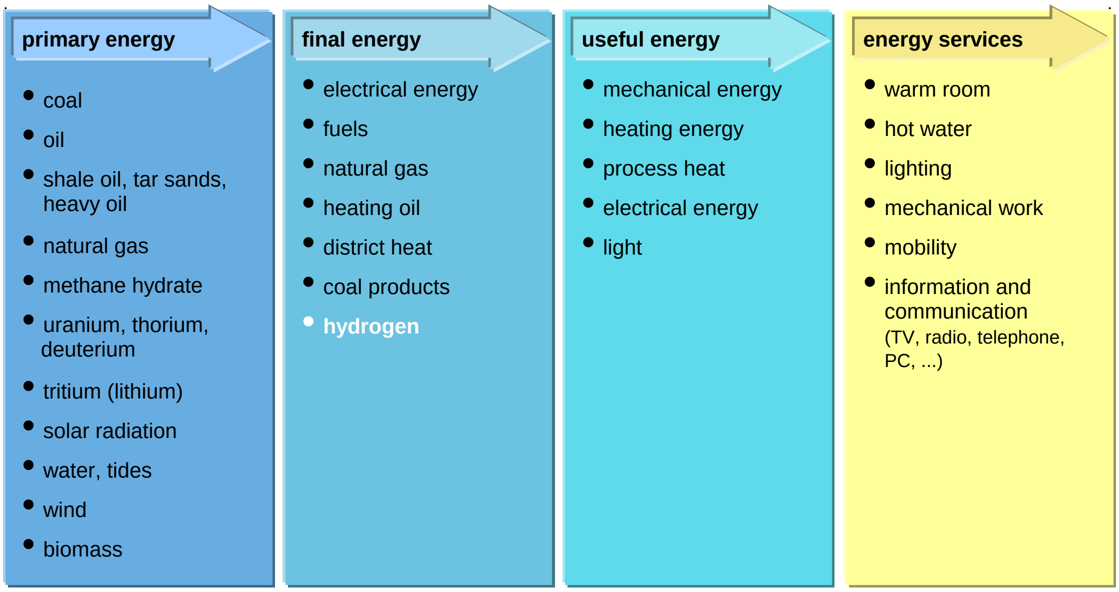


Figure 1-2: Stages of energy conversion

The large-scale production of hydrogen or hydrogen-rich gas is economically meaningful in the energy sector, if it represents a contribution towards conserving depletable resources or leads to reduced greenhouse gas emissions. This applies, in particular, to H_2 production from renewable energy, unless this energy can be otherwise directly integrated into existing supply structures.

The advantages of hydrogen use in the energy sector will take full effect when the use of renewable energies has reached a level that requires considerable (seasonal) storage: universal production possibilities, storage and transport with high utilization rates as well as low environmental pollution at the place of use. The variety of production and utilization possibilities opens up a wide range of technical solutions. This flexibility makes it possible to adapt to regional, ecological and economic requirements.

In principle, the conversion chains with the highest energy efficiency and the lowest losses should first be used. It should be noted that for the provision of hydrogen there are competing conditions of use for the primary energy carriers with only limited availability. On the one hand, electricity from renewable sources can be directly fed into the public grid. On the other hand, due to its storage capability, hydrogen has an advantage over electricity, which makes its use in mobile applications and for the transmission of, for example, offshore wind energy attractive and can thus justify the additional expenditure on energy conversion.

Sustainable energy supply is the basis for a higher quality of life. The challenge consists in a clean, safe and reliable provision of energy at affordable prices. Supply systems which do not adequately fulfil these requirements will have a lastingly negative effect on environmental and health conditions and will also fall behind for economic reasons.

Against this background, the following driving forces for dealing with the topic of hydrogen can be identified from the present perspective:

- security of energy supply and independence of energy imports can in future contribute to price stability
- hydrogen-based technologies (production, transport, storage, application) as export products can strengthen the competitiveness of German industry
- air quality and health protection are improved by a decrease in pollutant emissions
- global climate protection is taken into account by decreasing greenhouse gas emissions

Security of energy supply

Present-day energy supply is based on a marketable and uninterrupted provision of affordable fossil and nuclear energy carriers. Primary energy consumption in Germany involves a high percentage of fossil energy carriers with mineral oil products being predominantly used for mobile applications while hard coal and lignite form the basis for approx. 50 % of German electricity production. With the Federal Government's decision to opt out of nuclear energy, a further increase of the share of fossil energy carriers in total supply has to be assumed in the medium term. The CO_2 reduction targets also adopted in the Kyoto Protocol can thus only be reached by a combination of intensified measures for efficiency increase and – where economically meaningful – by substituting lower-carbon or renewable energy carriers.

In its Green Paper on supply security[1] the European Commission has identified the trend of Europe's increasing dependence on oil and gas imports.

It is being predicted that the EU's supply dependence on oil and natural gas will further grow from approx. 50 % today to about 70 % in 2030. Renewable energies and hydrogen provide the opportunity to broaden the basis of domestic energy sources and to thus counteract this trend of supply dependence.

Hydrogen can be produced from many sources, from fossil energy carriers as well as via the nuclear process chain and the use of renewable energy sources. Hydrogen and electricity together allow a higher flexibility to stabilize the generation grid composed of centralized and decentralized units and in specific cases increasing fluctuating infeed. The currently high dependence on oil could be reduced by using hydrogen in the transport sector.

However, a broad-based use of hydrogen for mobile and stationary applications requires considerable production capacities. At present, the global consumption of hydrogen is estimated at 500 billion Nm^3/a corresponding to 5.4 EJ/a, which in terms of energy is a negligible contribution (for comparison: primary energy consumption worldwide is approx. 2,400 EJ/a). Just about half of this hydrogen is directly used for energy generation, generally as non-pure waste

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[1] COM(2000)769, Green Paper towards a European strategy for the security of energy supply

product from chemical processes. The main application in the non-energy sector is ammonia production, for which one third of the hydrogen production is used.

In order to establish hydrogen in energy supply systems on a larger scale in future, considerable technological efforts concerning the production capacities are required. The production incentives are ultimately governed by the development of fossil energy carrier prices and the importance attached to supply security. Hydrogen production by coal gasification with subsequent CO_2 separation and storage basically represents an interesting option for European countries with major coal deposits. Renewable energies such as biomass, wind and tidal power can be used with different efficiency in Europe, depending on their regional availability. For example, a cost-efficient hydrogen production based on large solar thermal power plants can in future only be operated meaningfully in Southern Europe. Wind power utilization has already considerably increased in recent years above all in Germany and represents a further option for hydrogen production.

Competitiveness

The development and sale of energy systems and energy applications with high energy efficiency – from laptops, mobile phones, household appliances through automobiles up to complete power plants – represent an important economic factor for German industry. This applies both to covering the demand for energy services in the most cost- and energy-efficient manner possible and to the development of exportable products that provide a marketable added value due to significantly higher efficiency compared to standard technologies.

For strengthening the competitiveness and maintaining the industrial performance level the advancement of applications with high energy efficiency at affordable prices is indispensable in the context of globalized competition.

Technologies based on hydrogen can contribute an added value here. It should be borne in mind, however, that hydrogen-based mobile and stationary applications first have to become established compared to the in part highly efficient conventional systems. This also applies above all in comparison to direct electricity applications, where the use of hydrogen must represent an advantage.

Air quality and health protection

The technological development for stationary and mobile combustion systems has already achieved considerable progress in the past in coping with the problems of acid rain, dust and ozone pollution. Further improvements are socially necessary and politically desired. This will require additional efforts at technologically advancing the existing systems.

Hydrogen-based technologies for vehicles and power-generation facilities are nearly emission-free and can contribute towards reducing noise pollution in certain fields of application. In large conurbations, hydrogen-fuelled vehicles can contribute towards limiting local air pollution.

Global climate protection

With the Kyoto Protocol Germany has committed itself to reducing greenhouse gas emissions by 21 % between 2008 and 2012 compared to 1990. In the long term, a necessary further reduction is only possible by decarbonization, i.e. a lower-carbon energy carrier structure. Hydrogen produced CO_2-free or CO_2-neutral can make a contribution here.

The time at which CO_2-free hydrogen production will be feasible on a large technical scale and the order of magnitude aimed at is assessed quite differently. If the focus is on climate protection issues alone and assuming sufficient availability of fossil energy sources over the next decades and a primary, direct use of electric energy, economically significant contributions by hydrogen may not be expected before the fourth or fifth decade of this century[2]. Assuming, in contrast, an oil and gas shortage exacerbating much earlier in conjunction with the climate protection requirements, the introduction of hydrogen especially also in the transport sector will have to take place much earlier. On a global scale, an entry into the hydrogen economy for reasons of climate protection can take place earlier if, for example, there are sufficient use potentials for renewable energies or clear signals are given by other driving forces (e.g. reduction of urban air pollution).

1.2 National activities and initiatives

Federal Government activities

The Federal Government has supported research and development in the field of hydrogen technologies for more than twenty years. Funding culminated in the years 1988 to 1995, when the development of individual technologies, e.g. for the production of hydrogen by electrolysis and for storage, as well as demonstration projects were funded. Much attention was given to the binational HYSOLAR project, in which solar hydrogen production in Germany and Saudi Arabia was demonstrated, and to the solar hydrogen project in Neunburg vorm Wald already funded in the eighties by the Federal Ministry of Education and Research and the Bavarian Ministry for Economic Affairs, Transport, Infrastructure and Technology.

These research activities have shown that the necessary components for a hydrogen economy are available and the technology is controllable, but that there was no constraint for action on the energy economy to introduce a (solar) hydrogen economy. The greatest obstacle was the high cost of hydrogen production with renewable energies, especially photovoltaics.

The Federal Government then focused support on the technology field of fuel cells, since these have also many applications independent of a hydrogen economy. In the years from 1990 to 2003, research and development projects on stationary and mobile applications were supported with funds to the amount of € 180 million. Funding in the field of fuel cell technology culminated in the Federal Government's “Investing into the Future Programme” (Zukunftsinvestitionsprogramm - ZIP). Since 2001 additional funds have thus been available for also supporting research and development projects with a demonstration character.

For the further strategic orientation of the research activities on fuel cell applications, the Federal Government set up the BERTA working party, in which representatives from industry, science, the federal and state governments jointly discuss the guidelines of future developments. This strategy paper on hydrogen technology was also prepared in close cooperation with the BERTA working party.

Federal state initiatives

In parallel to the Federal Government, some federal states also support research and development projects. There have been state initiatives in Baden-Württemberg, Bavaria and North Rhine-Westphalia for a number of years, which stimulated hydrogen and fuel cell projects with a budget of more than € 150 million. In Hamburg, Hesse, Mecklenburg-Western Pomerania, Lower Saxony, Saxony and Saxony-Anhalt, institutions for funding hydrogen and fuel cell technology were also established recently (see also Annex).

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[2] cf. results of the Enquête Commission on "Sustainable energy supply against the background of globalisation and liberalisation", Berlin, 2002

Hydrogen demonstration projects

In order to support the political and social acceptance of sustainable fuels, their everyday suitability is demonstrated in various projects. This includes, in particular, the hydrogen filling station at Munich airport (ARGEMUC), the project "Clean Urban Transportation for Europe" (CUTE) and the Berlin "Clean Energy Partnership" (CEP), demonstrating the production, handling and use of hydrogen as a fuel in road traffic. In these field tests, a number of technical and economic issues, such as the safe refuelling of vehicles, the form of hydrogen storage and low-cost production, are being clarified. CEP is intended to demonstrate the production of fuels from renewable sources and their use in road traffic.

Industrial alliances

In Germany, the hydrogen and fuel cell industry has joined forces in the following initiatives, among others, in recent years: Fuel Cell Europe (FCE), German Hydrogen and Fuel Cell Association (DWV), Fuel Cell Initiative (IBZ), the Fuel Cell Expert Committee of the Association of German Engineers (BREZEL) and the Fuel Cell Forum at the Association of German Machinery and Equipment Constructors (VDMA).

Furthermore, there is the Transport Energy Strategy (TES), a partnership project of the German vehicle and mineral oil industry[3] and the German federal government. The lead goal of this project is to jointly evolve a strategy that will enable Europe to attain an international top position in the production and use of alternative energies for road traffic. Further strategic goals are to significantly reduce the dependence of traffic on oil, to conserve finite resources and to reduce emissions, especially CO_2. A transition strategy leading from present-day fuels through complementary or renewable fuels to hydrogen, besides other options (e.g. synthetic fuels from biomass), is currently being evolved as a long-term solution.

1.3 International context

At the **European level**, hydrogen programmes are being fostered and coordinated on a European scale by the Commission, primarily represented by the Directorate-General for Research, but also by the Directorate-General Energy and Transport and other Directorates-General. Thus, R&D and demonstration projects on hydrogen technology, in which Germany has a decisive share, are also supported under the 6th EU Framework Programme for Research and Technological Development.

In order to combine all European R&D activities and accelerate the market introduction of fuel cells and hydrogen, the European Hydrogen and Fuel Cell Technology Platform (H2/FC TP) was established in January 2004 by the European Commission at the recommendation of a High Level Group. H2/FC TP is steered by an Advisory Council representing all stakeholders, which is clearly dominated by industry. Germany's industry and science are well represented by ten out of 36 members (Ballard Power Systems AG, BMW, DaimlerChrysler, Linde, Siemens, Umicore, Research Centre Jülich, UITP, WWF, ZSW) and a deputy chairman also comes from Germany. The following working and ad-hoc groups of the Advisory Council are led by German representatives: "Strategic Research Agenda", "Deployment Strategy" and "Training and Education". In addition, the Member States Mirror Group within H2/FC TP, in which Germany is represented by the Federal Ministry of Economics and Labour, will introduce the concerns of the governments of the member states and regions.

The European High Level Group has devised a vision of the hydrogen energy economy in Europe (cf. Figure 1-3), which will serve H2/FC TP as a suggestion for a European hydrogen and fuel cell roadmap.

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[3] TES members: BMW, BP (Aral), DC, Shell, GM, MAN, RWE, Total, VW

An EU Hydrogen and Fuel Cell Quick Start Initiative promoted by the European Commission is to be provided with a budget of € 2.8 billion for a period extending beyond 2010. The exact priorities, contents and structure of this initiative are currently being evolved by the European Commission together with H2 / FC TP. One of the proposals is a demonstration plant for hydrogen production from fossil energy with CO_2 separation and storage as well as "hydrogen settlements", in which the feasibility of hydrogen as an energy carrier is to be explored from safety aspects up to economic efficiency. However, no budget has been determined as yet, and a large portion of the budget is to be provided by private investments.

The European HyWays project is concerned with drawing up a European roadmap for mobile and stationary hydrogen applications. The industrial and institutional partners of this EU-supported project will investigate the technical and also socio-economic conditions for the introduction of hydrogen as a future energy carrier in coordination with the European Hydrogen and Fuel Cell Platform. By comparative analyses of regional hydrogen supply options and energy scenarios it will be attempted to combine the national activities in a synthesized European hydrogen roadmap. Time horizons are the transition period until 2020 with a visionary outlook at 2050.

Furthermore, the political concept of the European Research Area (ERA) should be mentioned, which aims at coordinating European research in all fields in the form of networks. This coordination, designated ERA-NET, is currently being actively prepared for hydrogen and fuel cells under German leadership. It is planned to integrate a support for the already mentioned Mirror Group in the HY-CO work programme.

Internationally, in addition to the long-standing active cooperation under the Implementing Agreements of the International Energy Agency and other IEA activities, there is the International Partnership for the Hydrogen Economy (IPHE) instituted by the USA. The IPHE was founded in November 2003 with the aim of accelerating the introduction of the hydrogen economy. Germany is a founder member and has co-chairmanship in the Implementation and Liaison Committee. The Committee is to define concrete activities and projects under the auspices of IPHE, on the one hand, and seek relationships with the private sector, on the other. IPHE was signed by 14 states[4] and by the European Commission.

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[4] Australia, Brazil, Canada, China, France, Germany, Island, Italy, Japan, Norway, Russia, South Korea, United Kingdom, USA.

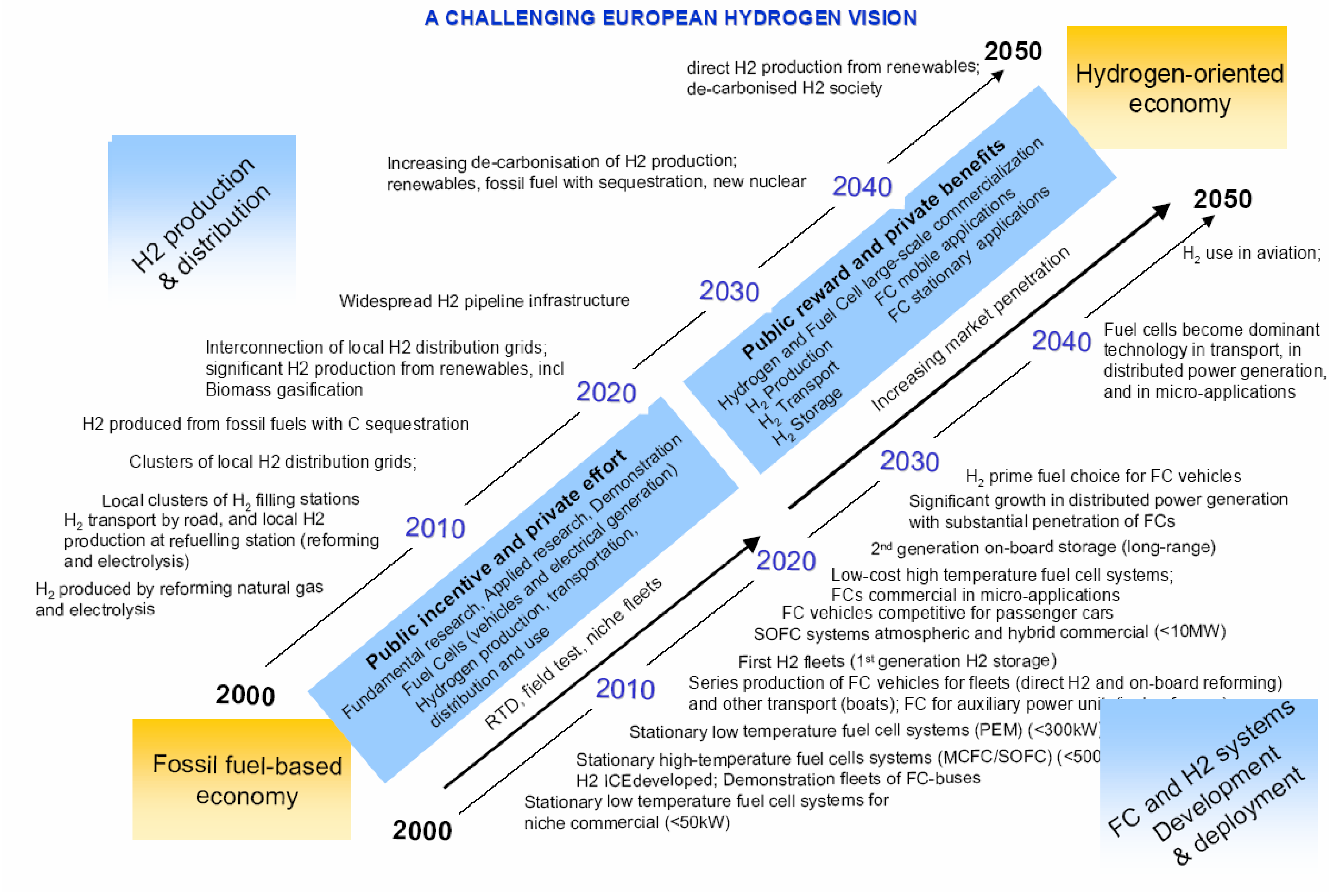

Figure 1-3: The European High Level Group's vision of a hydrogen economy

2 State of the art and need for research

Hydrogen is a globally used feedstock and commercial product in the petrochemical industry, the food industry, in flat glass production, in the electronics industry and others. Handling hydrogen has been a proven technology there for roughly one century.

About half of the hydrogen produced in Germany (approx. 20 billion Nm^3/a) is produced from natural gas and naphtha. The other half is a byproduct in refineries and is largely used there for hydrogenation. A small fraction (approx. 2 %) is a byproduct of chlorine-alkali electrolysis.

Large plants for hydrogen production from fossil energy carriers reach a daily capacity of more than 4 million Nm^3/d. They can in principle also be used for the production of hydrogen from biogenic resources. Electrolytic water splitting is used, in particular, for the production of high-purity hydrogen and only has a share of roughly 5 % in the total volume. Broken down according to primary energy carriers, 45 % of the hydrogen is produced from crude oil, 33 % from natural gas and 15 % from coal. The remaining 7 % come from electrolysis.

The experience gained with the "non-energy" and "indirect-energy" use of hydrogen concerning the production, transport and safe handling of large amounts of hydrogen is also of great significance for a future use of hydrogen as an energy carrier. This applies, in particular, to water electrolysis, which may be one of the most important production methods in a future hydrogen economy. At some international locations with low-cost electricity from hydropower, major electrolysis plants with connecting capacities of up to 150 MW (corresponding to 33,000 Nm^3/h of hydrogen) have already been operated for decades.

2.1 Hydrogen production

2.1.1 Energy supply for hydrogen production

2.1.1.1 Fossil sources

The energy needed for hydrogen production will have to be primarily provided by fossil fuels in the foreseeable future, since low-cost renewable energies are not yet sufficiently available. Besides using coal, natural gas or other hydrocarbons in chemical processes, electric current from fossil-fired power plants can also be used for hydrogen production. In order to keep CO_2 emissions as low as possible, a range of measures must be taken and research and development for relevant power plant technologies advanced. The following is required for low-CO_2 energy supply:

1. An increase of power plant efficiency, so that more energy is provided with the same raw material input and CO_2 emissions.
2. The separation of CO_2 from the exhaust gas and subsequent storage. For this purpose, above all, the IGCC process (integrated gasification combined cycle) and oxyfuel processes (combustion with pure oxygen) are being developed.

The exact state of the art and the research priorities recommended as well as the technology availability to be expected were described in detail in the COORETEC report.

2.1.1.2 Renewable sources

Renewable energies enable a sustainable and practically emission-free hydrogen supply. Among the renewable sources, especially wind and biomass are of relevance in Germany. In generating electricity from these sources, however, the electric current should preferentially be used directly for reasons of efficiency.

But there is also a potential for H_2 production: the at present already high share of fluctuating wind power fed into the grid leads to high regulation and standby management expenditure. In case of a further massive expansion of wind power on- and offshore, these requirements will further increase. Apart from the conventional option of additional grid and regulating power plant construction, the production of hydrogen from wind power that cannot be fed into the grid is an alternative here. In particular, the planned offshore wind farms could thus contribute to H_2 production. Electrolysis can also be used as a variable load in the electric grid to support the increasing demands made on regulating capacity.

Biomass is another potential renewable energy carrier for H_2 production. Biomass can either be converted by conventional power plant processes into electricity and then by electrolysis into H_2 or directly used for H_2 production via gasification processes. In using biomass, however, competing uses must be taken into account (food and feed, extensification of agriculture, nature conservation, industrial use). A sound analysis of the biomass pathways available for H_2 production is therefore required.

Other renewable sources such as solar energy or geothermal power are of minor significance in Germany as yet. Before considering these sources for H_2 production, their use for electricity generation should have reached an economically attractive order of magnitude.

Fuel for private transport represents a high-price segment in comparison to other useful energies. If CO_2-free fuels (hydrogen from renewable sources) are adequately funded, e.g. via lower tax rates, a pull effect can be triggered for renewable energies, i.e. the further expansion of renewable resources is supported.

2.1.1.3 Nuclear sources

Nuclear energy also basically provides a CO_2-free energy carrier for H_2 production. Due to the Act on the structured phase-out of the utilization of nuclear energy for the commercial generation of electricity, however, this resource cannot be used for H_2 production in the long term in Germany according to the present state of affairs.

2.1.2 Hydrogen production processes

2.1.2.1 Electrolytic hydrogen production

The production of hydrogen via water electrolysis by means of electric current considerably increases the possible resources for hydrogen supply, since electricity can be produced from nearly all primary energy sources. The requirement for a diversification of the sources for energy supply is thus accommodated. However, the total chain of the provision of energy must also be considered here with respect to emissions and efficiency. If fossil sources are used, the CO_2 emissions must be adequately reduced, for renewable sources of electricity the electric current should be primarily used directly, but (local) overproduction may be used for H_2 generation. In regulating the electric grid, a challenge that is gaining significance with increasing infeed of fluctuating generation, electrolysis can also take over grid regulation tasks.

Hydrogen can be directly produced from direct current by the electrolytic decomposition of water. Hydrogen and oxygen are produced as high-purity gases (typical value: 99.8 %, with steam impurities and traces of oxygen or hydrogen and nitrogen) during electrolysis. Electrolytic hydrogen can therefore also be directly used in membrane fuel cells for reconversion into electricity without any further fuel gas cleaning. Due to their modular design consisting of electrochemical single cells, electrolytic processes for hydrogen production also achieve very high conversion efficiencies in small-sized systems.

Three process variants for electrolytic hydrogen production from water are possible and differently far advanced:

- "Classical" and most advanced alkaline water electrolysis with aqueous potash lye as the electrolyte at an operating temperature around 80 °C.
- Membrane electrolysis with a proton-conducting membrane as the electrolyte, whose design is basically comparable to that of a membrane fuel cell and which also works at an operating temperature of about 80 °C.
- High-temperature steam electrolysis ("Hot Elly") developed by Dornier and operated in the first laboratory models, where the basic principle is the use of oxygen ion conductors as the electrolyte at operating temperatures between 800 and 1,000 °C, comparable to the solid oxide fuel cell.

GHW is currently developing a 30-bar pressure electrolyser, in which all essential pressure components (cell stack, separator) are integrated in the pressure tank. The aim is to significantly reduce the complexity of the overall system leading to cost reduction, efficiency increase and less space requirement. A first prototype is in test operation.

In the electrolytic processes of the chemical industry (chlorine-alkali electrolysis, hydrochloric-acid electrolysis) hydrogen is released as a byproduct in considerable quantities. Due to the further development of these processes, however, the amount of "excess" hydrogen in these chemical processes will significantly decrease in the medium to long term.

Status and development potential of alkaline water electrolysis

Alkaline water electrolysers are nowadays used above all for the local provision of hydrogen for chemical processes (metallurgy, fat hardening, electronics industry) in regions where electric energy is available at favourable prices.

The capacity of the plants has reached production volumes of several hundred up to more than 33,000 Nm/h. With the exception of the 30-bar pressure electrolysers developed by GHW and Lurgi, alkaline electrolysers are operated near atmospheric pressure up to a few bars overpressure. The efficiencies of the conversion of electric energy into hydrogen are between 65 and 70 % (relative to the upper heating value of hydrogen) for classical, alkaline electrolysis.

In the 1980s, a number of research programmes were carried out with the aim of increasing the efficiency of advanced alkaline water electrolysers. It was found that plasma-technical electrode activation leads to a significant efficiency increase, so that technical efficiencies above 80 % have meanwhile also been reached in industrial application with proven lifetimes of more than 40,000 hours. Within the framework of the HYSOLAR project it was demonstrated that with an optimum design average efficiencies of more than 85 % can be achieved for hydrogen production from fluctuating primary energy.

Alkaline electrolysis modules have recently been increasingly used in international projects for the hydrogen supply of vehicles from decentralized systems or mobile supply stations. However, the efficiencies achieved here are clearly below the technical values specified above.

Status and development potential of membrane electrolysis

A central aim of the development of membrane electrolysers is the on-site provision of hydrogen as a fuel. PEM high-pressure electrolysers with an operating pressure of 35 MPa and a production rate of 2.5 Nm^3/h are already available on the market. Electrolysis modules with 30 Nm^3/h at 40 MPa hydrogen pressure are under development for the decentralized supply of filling stations. A further pressure increase to 70 MPa, the planned upper limit for hydrogen storage tanks in vehicles, is being aimed at.

A central aspect in the safety-engineering control of electrolysers is the avoidance of an ignitable hydrogen-oxygen mixture. With rising pressure the solubility and lateral diffusion of the reaction gases increases in the electrolyte and thus the danger of a mixture being formed. This problem can also occur in the case of an electrolyte membrane fracture. For this reason, a thorough analysis and licensing evaluation of PEM high-pressure electrolysers is required.

Status and development potential of high-temperature steam electrolysis

In high-temperature electrolysis, an oxygen-ion-conducting solid electrolyte similar to that of the SOFC high-temperature fuel cell is used and the operating temperature of 800 - 1,000 °C is also in the same range. The advantage of this process is that for splitting steam that is supplied on the cathode side less electric energy is needed than for splitting water. Moreover, the vaporization enthalpy of water can be thermally supplied, which opens up new forms of energy that can possibly be provided more easily (e.g. solar thermal energy).

A new process variant of high-temperature steam electrolysis in the temperature range from 700 to 800 °C, called NGSA process (natural gas assisted steam electrolyser), uses the partial oxidation of natural gas to synthesis gas on the anode side. In this case, no oxygen evolves on the anode side, but the oxygen is directly used for the partial oxidation of hydrocarbons. The low electrochemical potential of this "natural gas consuming anode" permits very low cell voltages for steam electrolysis from the thermodynamic perspective and thus a high efficiency. The realization of the NGSA concept so far only tested in the laboratory still poses numerous material problems which, however, are also closely related to the development work for high-temperature steam electrolysis or the solid oxide fuel cell. The reduction of the operating temperature to 700 - 800 °C along with sufficient oxygen ion conduction and the fabrication of homogeneously tight ceramic membranes as well as gas diffusion electrodes resistant to ageing should be mentioned here as examples.

System-engineering aspects of integrating electrolysers into electric grids and for direct operation with fluctuating electricity supply

An interesting system-engineering aspect of electrolytic processes for the production of hydrogen with electric energy is the possibility of load management in electric grids or locally at the consumer. Like all electrochemical energy converters electrolysers can respond to load changes almost instantaneously. Highly dynamic electrolysers can thus be used for hydrogen production both in the case of fluctuating excess supply (e.g. during prolonged, rising renewable electricity production) and in the case of demand deficiencies on the consumer side during low-load periods. In combination with a hydrogen storage tank, an electrolyser can be used for load management in the same way as a variable electricity consumer. This load management can lead to a higher total utilization rate for power plants, since generating capacities must be reserved to a minor extent for regulating tasks.

Need for research

The problems encountered in the development of water electrolysis are by their nature closely related to fuel cell research needs.

- For low-temperature electrolysers, the reduction of the oxygen overvoltage by improved oxygen catalysts offers a potential for increasing the efficiency by up to ten percentage points.
- For system engineering it is necessary to develop clearly less expensive electrolysers by greatly simplified system concepts (gas separation) for e.g. on-site production at filling stations or intermittent operation, for instance, directly connected to wind power plants.
- For high-temperature electrolysers, as in the case of the SOFC, materials development is given priority in order to clearly increase the operating and service times.

2.1.2.2 Steam reforming of hydrocarbons

State of the art

Hydrocarbons can be converted into mixtures of hydrogen, carbon monoxide, methane and carbon dioxide by the reaction with steam. Technically, this is called steam reforming and means the endothermic catalytic conversion with steam above 800 °C.

Due to the catalysts applied, it is absolutely necessary to use clean feedstocks that can be vaporized free from residues. Hydrocarbons ranging from methane to gasoline can be used here.

Development potential

Steam reforming of light hydrocarbons is the most widespread process worldwide for producing hydrogen today. The development of steam reforming with respect to technical and economic optimization is thus relatively far advanced. The overall efficiency of existing plants is in the range of 70 - 80 %. Nevertheless, the U.S. Department of Energy, for example, expects an efficiency increase by some percentage points and a cost reduction of 25 to 30 % by the future integration of CO_2 separation or the use of improved catalysts.[5]

From the energy and economy aspect, further improvements for future plants are above all expected by optimum system integration with the combined production of hydrogen, electricity and heat. Another important development goal of current optimization measures is the reduction of CO_2 emissions from the plant.

2.1.2.3 Partial oxidation of heavy oil

State of the art

Heavy hydrocarbons can be converted into hydrogen with the aid of partial oxidation. This process is mainly used for the production of hydrogen from heavy oil and sulphur-containing organic residues. Partial oxidation involves an exothermic conversion of heavy oil with oxygen and the addition of steam. The chemical reactions proceed best at temperatures between 1,300 and 1,500 °C and a pressure from 30 to 100 bar without having to use a catalyst. In contrast to steam reforming, partial oxidation does not make any special demands on the quality of the feedstocks. In practice, the partial oxidation of heavy oil has been realized in two large-scale processes by Texaco and Shell.

Development potential

From the energy and economy aspect, further improvements for future plants are above all expected by optimized system integration. It may be assumed for the future that the fuel input can be reduced by approx. 5 % and the electricity input by about 10 %, so that the plant utilization rate would increase from currently approx. 73 % to roughly 77 %.

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[5] U.S. Department of Energy: Hydrogen Program 2000

2.1.2.4 Gasification of coal and biomass

A combination of pyrolysis and gasification is used for the production of hydrogen from solid fuels. The gasification of solid fuels for the industrial production of gases has been performed in the past using a variety of processes. The large number of reactor options is due to the large number of influential factors providing a wide scope for process design.

The gasification techniques can be differentiated according to the following criteria:

- external and internal heat generation (allothermal or autothermal gasifier)
- contact between oxidant and fuel (fixed bed, fluid bed and entrained bed)
- direction of the mass flows of fuel and gasification medium (co-flow/counter-flow)
- gasification medium (air, oxygen, steam or a mixture)

State of the art for the gasification of solid fuels

The procedure for the conversion of solid fuels into hydrogen is largely fixed: high-temperature gasification (fluidized-bed and entrained-bed reactor) for producing a synthesis gas from which hydrogen can be produced by conventional and available technology. This means that fixed-bed gasifiers are not suitable for hydrogen production.

Development potential of solid fuel gasification

Within the framework of an extensive project of VEBA OEL AG, the conversion of solid fuels into hydrogen as an energy carrier was pursued in the years 1989 to 1994. In this context, suitable gasification processes were developed and in part tested on a technical scale. The results of these studies, which are largely based on simulation calculations, promise a considerable optimization potential with respect to efficiency.

A utilization rate of up to 70 % can be achieved for hydrogen production with the analysed processes being optimized in terms of process engineering. The use of the waste heat produced is of decisive influence on the energy efficiency of a gasification unit. According to the present state of the art, for example, the hot raw gas must be cooled in a tubular fume cooler. The thermal energy can be used for the generation of process steam, for which, however, suitable heat consumers are required.

2.1.2.5 Kvaerner process

Hydrocarbons can be converted into hydrogen and high-purity carbon in a plasma arc at temperatures of 1,600 °C by means of electricity. No direct carbon dioxide emissions occur here due to the special process conditions. A pilot plant for this so-called Kvaerner process produces 500 kg/h carbon and 2,000 Nm^3 hydrogen from 1,000 Nm^3/h natural gas with an electricity input of 2,100 kWh. The overall efficiency is thus approx. 50 %.

2.1.2.6 Other processes

Thermochemical hydrogen production

The thermally activated decomposition of water into hydrogen and oxygen begins at temperatures above 2,200 °C. By the input of heat at a very high temperature level it is thus possible, in principle, to directly produce hydrogen from steam. Apart from technically controlling the necessary operating temperature, the basic and so far unsolved problem is the separation of hydrogen at these high temperatures.

A decrease of the temperature of thermal water splitting below 900 °C can be achieved by coupled chemical reactions. As early as in the 1970s various thermochemical cycles were proposed for the input of heat from high-temperature reactors, and these are in part also suitable for the utilization of concentrated solar radiation. From the present perspective, an improved sulphuric acid iodine process exhibits the highest system efficiencies and the greatest potential for improvements: iodine and sulphur dioxide react with water at 120 °C forming hydrogen iodide and sulphuric acid. After separation of the reaction products, sulphuric acid is split into oxygen and sulphur dioxide at 850 °C, and hydrogen and the base product iodine are produced from hydrogen iodide at 300 °C. The high thermal efficiencies of the thermochemical cycles (up to 50 %) must be compared to the still largely unsolved material and process-engineering difficulties.

Basic development work on thermochemical hydrogen production is currently being performed under the 5th and 6th EU RTD Framework Programmes, in which processes for the use of waste heat from high-temperature reactors as well as the use of concentrated solar radiation are examined. Even if the time perspective for these processes extends far into the future, the fundamental problems to be solved here are of considerable significance. Process-engineering issues of high-temperature technology and the solution of materials problems as well as the development of high-temperature separation processes for hydrogen are also of relevance in other areas of energy technology such as coal or biomass gasification.

Photochemical conversion

Apart from the use of solar energy in thermochemical processes, the possibility of producing hydrogen by photochemical reactions is being explored. The basic idea is to directly use solar radiation by having energy-rich photons absorbed by reactants. This requires semiconductor materials, whose energy gap is so large that electrons can be extracted from the water by the uptake of light quanta, which leads to water splitting.

The thus excited conversion processes are to be facilitated or enabled by the use of photocatalysts. The main problem is that the photoactive materials must be catalytically highly active and at the same time of long-term stability in contact with water. In the long term, the combination of photo- and thermochemical processes also seems to be promising.

Biological hydrogen generation

A technology which is also at an early stage of research is biological hydrogen generation, in which hydrogen is produced by microorganisms in biological processes. In the years from 1989 to 1994, a comprehensive research programme was dealt with on this range of topics in Germany. Even though the techniques derived are not yet competitive with the established methods of hydrogen production, the level of knowledge attained permits biological hydrogen production to be demonstrated on a laboratory scale and optimization strategies to be experimentally explored.

The central step in all processes for biological hydrogen production is the enzymatic conversion of protons and electrons into molecular hydrogen. The possible metabolic pathways can be divided into three processes: biophytolytic hydrogen production by green algae, photoproduction of bacteria and fermentation of biomass.

The starting process of **biophotolysis** is photosynthesis, in which water is split into oxygen, protons and electrons (water splitting) with the aid of sunlight. Normally, the electrons set free in this process are then used for building up biomass together with atmospheric carbon dioxide. However, certain green algae and cyanobacteria are also capable of transferring the electrons to protons thus forming molecular hydrogen. The great advantage of this process is that only water is needed as the starting material. This is of particular interest for the realization of technical processes, on the one hand, and opens up new prospects for producing hydrogen with the aid of water and solar energy only without any release of CO_2, on the other.

In contrast, **phototrophic bacteria** (purple bacteria) need a culture medium of organic substances. These bacteria, which belong to the group of anoxygenic phototrophic bacteria, are able to reduce the protons obtained from suitable organic compounds (for example, biomass) and give them off in the form of gaseous hydrogen. Under optimized conditions, purple bacteria can currently achieve production rates of roughly 150 l H_2/h per kilogram of biomass, which corresponds to a conversion of about 70 % of the theoretical maximum.

The combination of algae and purple bacteria in a combined reactor for hydrogen production seems to be very promising. In a two-stage process, green algae first bind CO_2 and build up carbohydrate after photosynthesis, which is then converted by purple bacteria into CO_2 and H_2 in the second step. In a closed CO_2 loop, the first stage so to speak provides the nutrient for the second process in which hydrogen is produced. On balance, hydrogen and oxygen are thus produced from water and sunlight.

Unlike the biological hydrogen production processes so far described, **fermentation processes** are independent of sunlight. They produce hydrogen from energy-rich organic substances with the aid of microorganisms. In terms of process engineering, fermentation processes have the great advantage of being simple to establish and proceeding in closed vessels without major technical outlay. Moreover, a large number of different organic feedstocks can be used for hydrogen production.

A fundamental difficulty of fermentation processes is that, in addition to the conversion of sugar into H_2 and CO_2, in reality a considerable portion of organic acids, alcohols and ultimately methane is formed, so that the hydrogen yield remains low. Besides understanding the processes that take place, research must therefore continue to look for suitable thermophilic bacteria and explore the optimum boundary conditions for hydrogen production.

Table 2-1: Need for R&D in the field of H_2 production

Process	Need for R&D	
Electrolysis high-pressure electrolysis high-temperature electrolysis	• higher pressure levels • integrated concepts • materials, catalysts • efficiencies	cost reduction and series production
Steam reforming	• small reformers • H_2 quality • materials, catalysts • behaviour at partial load	
Coal gasification and partial oxidation		
Biomass gasification	• process optimization • materials • H_2 quality	
Kvaerner process		
Other processes thermochemical production photochemical processes biological processes	• basic research	

2.2 Hydrogen logistics

2.2.1 Gaseous hydrogen

2.2.1.1 Compression

Hydrogen compression is performed in analogy to natural gas compression. In part, even the same compressors can be used, provided that tightness is ensured by seals (e.g. Teflon) suitable for hydrogen gas (GH_2) and the compressed gas is free from oil. The technology is thus sufficiently proven and available.

New developments are above all concerned with an optimization of the units in the overall context, primary applications pursuing high-pressure compression at filling stations. Typical pressure levels are in the range of 3 to 4 MPa for the precompressor stage for filling a collection tank and up to 80 MPa for filling the storage tank of a high-speed refuelling system, high-speed refuelling being effected by overflow to a tank pressure level of approx. 70 MPa. The choice of the upper pressure level primarily depends on the maximum permissible filling pressure of the hydrogen storage tank.

The efficiency of present-day hydrogen compressors is approx. 80 %. Due to the logarithmic correlation of pressure and compression work, the additional energy requirement increases only insignificantly at higher filling pressure. Thus, for example, the compression from 0.1 to 30 MPa only consumes about 10 % more energy than the compression from 0.1 to 20 MPa.

All current natural gas compressors can also be used for hydrogen compression with minor adaptations, so that the whole range of small compressors with a throughput of a few Nm^3/h up to several hundred Nm^3/h is available. Primarily, compressors applied for filling stationary high- (70 - 80 MPa) or low-pressure storage tanks (1 - 5 MPa) may be used, and the rating of the upper pressure level can only be determined in connection with their use.

2.2.1.2 Long-distance pipeline transport

In principle, hydrogen in the same way as natural gas can be transported over long distances, e.g. from the production sites in the sunbelt to the consumption centres in Central Europe. Two special features must be noted for the transport of hydrogen: the density of hydrogen is only about one tenth of that of natural gas, so that only about one tenth of the transport losses of natural gas arise with the same volume flow. On the other hand, gaseous hydrogen only has about one third of the energy density of natural gas, so that the three-fold volume flow is required for transporting the same amount of energy.

State of the art

For the long-distance transport of natural gas, pipelines with nominal diameters of up to 1,420 mm and pressures of up to 80 bar are used today. With these pipelines, an annual transport capacity of up to 84 billion m^3 of hydrogen could be provided. The wall thickness of the pipelines is normally 20 mm of X70 steel grade. Higher-grade steels are also used depending on the place of application. Compressor stations are necessary at regular distances to compensate the pressure losses. The efficiency of a hydrogen compressor needed for pipeline transport for compression from 30 to 80 MPa is currently approx. 80 %.

Development potential

The development in pipeline construction proceeds towards higher pipe diameters, higher operating pressures and more efficient compressor stations based on combined processes. However, for economic reasons, the application of these new technologies is not necessary at present due to the security of natural gas supply achieved with the existing infrastructure. The situation is different for building up a large-scale hydrogen supply, because this will involve much larger gas volumes than current natural gas supply. It must thus be expected that pipe diameters of up to 1,600 mm and operating pressures of up to 120 bar will be needed in a hydrogen energy economy.

Due to the large pipeline volume it will be possible to store approximately the gas content of one full-load day in such a pipeline. The decrease of the pressure level at night and its increase during the day can be balanced in such a way that for solar-produced hydrogen the pipeline is only fed during daylight hours. Even without the use of additional storage tanks it is always possible to extract hydrogen from the pipeline in Germany. This type of floating operation has already proved efficient in long-distance natural gas supply for compensating load peaks.

2.2.1.3 Grid distribution

Analogously to natural gas, hydrogen can be distributed through a local grid. In contrast to the natural gas grid, there is no pipeline infrastructure for an area-wide distribution of hydrogen at present. For a future hydrogen energy economy it is conceivable and suggests itself to operate a distribution grid for hydrogen just as for natural gas, which would be created by building some new pipelines and modifying the majority of natural gas pipelines then no longer needed. Due to the lower density of hydrogen in comparison to natural gas, however, special precautions with respect to the tightness of pipes and apparatus would be required.

Similar to the natural gas grid, the hydrogen grid will be divided into supraregional distribution, regional distribution and local gas supply. Gas from the supraregional grid is available at a pressure of roughly 70 bar, so that the gas can be transported up to the final user. In the regional grid and in the local gas grid, which can be connected to the supraregional grid via throttles and expansion machines for pressure reduction, in addition to utilizing pipe breathing, gas storage tanks would also be needed for supply optimization. In the regional grid, compressor stations would have to be installed for keeping the pressure in peak-load times, whose energy requirements could be partially compensated by the operation of expansion turbines. Since hydrogen has only roughly one third of the energy density of natural gas, the volume flow must be tripled to maintain the same energy flow, which also increases the required compression effort. Due to the lower density of hydrogen, an increase of leakages must also be expected at the different grid levels and in storage tanks.

There are already major hydrogen pipeline systems in extensive chemistry locations in Belgium, Brazil, France, Germany, Thailand and the USA today. About 240 km of the total pipeline length of about 2,000 km is operated in the German Ruhr district and about 100 km in the Leuna-Merseburg region. Worldwide, these pipelines have different cross-sections and pressure levels (from roughly 10 bar up to 300 bar). Their safety standard is excellent and proven in industrial application.

2.2.1.4 Hydrogen gas filling station

The GH_2 filling station concept is based on the fact that GH_2 is stored in a compressed form, so that it only has to be transferred into the pressure tank of the vehicle during refuelling. The principal components of a GH_2 filling station are thus the compressor, the pressure storage tank and the actual gas pump. In addition, filter and cleaning systems for gas conditioning may be required.

The compressor is normally of multi-stage design and must meet increased tightness requirements due to the low density of hydrogen. The pressure tanks comprise several storage banks, so that the compressor can continuously feed gas into the tanks while GH_2 is extracted from another storage bank. The hydrogen is compressed to a pressure of up to 800 bar, so that it can be expanded to 700 bar in the pressure tanks of the vehicles to be refuelled.

The configuration of a GH_2 filling station is comparable to that of natural gas filling stations, but there are differences in the technical design due to the different physical properties of hydrogen and natural gas. The supply of a GH_2 filling station can take place either by on-site production (electrolysis, natural gas reforming) or in future, analogously to present-day natural gas filling stations, by connection to a GH_2 grid.

2.2.2 Liquid hydrogen

The special advantage of liquid hydrogen (LH_2) is its high volume-related energy density of roughly 2.36 kWh/l, which makes it interesting, in particular, for mobile applications.

2.2.2.1 Liquefaction

Hydrogen has to be cooled to about -235 °C for liquefaction. For this purpose, the gas to be liquefied is precooled to about 80 K in several steps using e.g. liquid nitrogen, until a temperature is reached at which the Joule-Thomson effect can set in. Further cooling down to the liquefaction temperature then takes place in several steps. During expansion to the liquefaction temperature only part of the gas stream becomes liquid. The remaining gas is used to cool an upstream stage and then compressed again. Catalysts must be used to accelerate the conversion of ortho into para hydrogen.

For the liquefaction of hydrogen, 0.97 kWh/kg of heat, the condensation enthalpy of 0.13 kWh/kg and the energy release of 0.2 kWh/kg from ortho-para conversion must be extracted from the gas. However, the theoretical minimum energy requirement of a liquefaction system is much higher due to the Carnot efficiency of the ideal cycle and ranges from 3.36 kWh/kg up to 4.42 kWh/kg, depending on the process flow and the boundary conditions.

State of the art

Industrially used liquefaction systems are based e.g. on the Claude process, in which the coldness required for the process is generated at three temperature levels by nitrogen (80 K), expansion turbines (80 - 30 K) and Joule-Thomson expansion (30 - 20 K). Ortho-para conversion is performed by catalysts at four different temperature levels. The liquefaction capacity of such plants is approx. 4,300 kg/d (corresponding to approx. 2,000 Nm^3/h) and the specific power requirement is 13.4 kWh/kg.

Development potential

The existing plants are by a factor of 20 to 30 too small for a future large-scale hydrogen production. For correspondingly larger plants equipped with the technology available today, a decrease of specific power requirements to about 10.5 kWh/kg may be expected. There is a further optimization potential of approx. 20 % by optimizing the refrigeration circuits, using magnetocaloric refrigeration processes and shifting ortho-para conversion to higher temperature levels with the aid of electromagnetic catalysts.

2.2.2.2 Long-distance shipping

If LH_2 is to be shipped on a large scale and over long distances, an integrated concept for a hydrogen infrastructure is needed. Three steps are to be distinguished here:

- loading the ships with LH_2 (loading)
- shipping
- unloading and interim storage in the port of destination

Loading

For transshipping liquefied natural gas (LNG) the liquefied gas is at present pumped ashore by submersible pumps arranged inside the tank. Such pumps are not available for hydrogen, especially in the capacity range required for fast transshipment. Moreover, the energy input into the liquid rises considerably with increasing handling rate and each energy supply to a liquid leads to undesirable evaporation near the boiling point. These considerations have led to the concept of also using the LH_2 tanks as storage tanks ashore instead of firmly installing them inside the ship. In this way, loading and unloading or filling LH_2 into the tanks are uncoupled. At the same time, two pumping operations with their inevitable losses are omitted and the use of ships and tanks becomes more flexible. Within the framework of the Euro-Quebec-Hydro-Hydrogen Pilot Project (EQHHPP) it was found that the boil-off losses in filling the storage tanks and loading the tanks can be completely avoided.

LH_2 shipping

The transport of liquefied gases such as LNG is state of the art. However, the transport concepts used for LNG are not or only to a limited extent applicable to LH_2 transport due to the low liquefaction temperature of 20 K. For this reason, two different concepts for shipping LH_2 have been developed within the framework of the Euro-Quebec project and of BMBF projects.

In EQHHPP floatable barges were envisaged for LH_2 transport, on which the tanks are mounted. The tanks are transported by a dock ship accommodating five of these barges. Since these tank barges are also to be used for storage ashore, they must be integrated in the infrastructure ashore.

For future large-scale hydrogen transport the SWATH ship concept suggests itself as an alternative. SWATH stands for small waterplane area twin hull. Characteristic of this ship concept are the two floating bodies of the more than 300 m long ship. They carry five spherical tanks in which a total of 115,000 m^3 of liquid hydrogen can be transported. The tanks are separately installed on laterally projecting platforms, so that they can be separated from outside the ship. The comparison of a large hydrogen tanker of the SWATH type with a large oil tanker of the same size shows that more than twice the tank volume and a multiple mass can be transported by the oil tanker. A crude oil tanker can transport roughly nine times as much energy despite the high energy density of liquid hydrogen. This shows that a high transport and thus traffic volume must be expected if hydrogen should have an appreciable share in energy supply.

In order to avoid losses from the ship's tank due to repeated cooling, the ship is kept at low temperature during return to the port of loading. For this purpose, a LH_2 residue is always left in the tank, so that the actual transport capacity is roughly 5 % below the nominal capacity.

2.2.2.3 Distribution by LH_2 truck

So-called "merchant hydrogen", that is hydrogen which is freely commercially available and not immediately used again or delivered to other consumers through pipelines, is supplied to the customer by rail, but in most cases by semitrailer. Pressure storage tubes (200 bar), cylinder bundles (200 or 300 bar - 300 to 530 kg H_2 per cargo) or cryogenic liquid hydrogen storage tanks with a maximum transport volume of 53,000 l (corresponding to 3,400 kg H_2) are used for transport on semitrailers. More than 200 million Nm^3 of hydrogen is thus transported annually on public roads in Germany.

2.2.2.4 LH_2 filling station

A LH_2 filling station essentially has the same plant components as a conventional filling station; the principal components are the LH_2 storage tank, the pump and the fittings and lines in between. All the components of an LH_2 filling station must be provided with a special heat insulation. State-of-the-art filling systems enable a refuelling process for 100 l LH_2 within two minutes, which is acceptable for customers, and also a fast sequence of several refuelling operations.

2.2.3 Pressure storage and liquid hydrogen storage

2.2.3.1 Pressure storage

Depending on the intended application, pressure storage tanks for gaseous hydrogen in principle differ in type and size. A differentiation is normally made between large stationary tanks, small stationary tanks and mobile tanks.

Large stationary tanks

For the storage of gaseous hydrogen in large tanks, solution-mined salt caverns or mined-out gas and oil deposits can be used. In comparison to natural gas storage, however, at least a doubling of the specific storage costs must be expected, since the triple storage volume has to be provided for the same energy content. The stores operated at pressures of up to 50 bar (salt caverns) typically have storage capacities of a few to several hundred million Nm^3.

Decentralized pressure storage

Pressure tanks as are used for the storage of natural gas are also suitable for decentralized storage. Depending on the application and dimensioning, stationary storage tanks (pressure tube tanks, vertical or horizontal tanks, spherical tanks) of different size are used here. The geometrical volumes of tank systems range from 5 to roughly 100 m^3 and hydrogen is stored here up to a pressure of 800 bar.

Mobile pressure storage

Pressure storage tanks of aluminium/CFRP are used for mobile applications. The geometrical volumes of these tanks range from 50 to about 400 litres and, depending on the application, several single tanks are generally connected forming a storage bank.
Ranges of approx. 150 km are possible today with the 350 bar pressure tanks of composite materials currently used in many prototype H_2 passenger cars. A range of more than 600 km, acceptable for customers, can only be reached with one hydrogen fill-up by further optimized 700 bar tanks.

2.2.3.2 Liquid hydrogen storage

Stationary storage

The storage technology for liquid hydrogen is state of the art today especially due to intensive applications in space flight. Storage is effected above all in storage tanks with perlite vacuum insulation. There are a large number of such tanks in the USA, the largest at NASA in Cape Canaveral. It has a storage volume of about 3,800 m^3 (approx. 270 t LH_2). With an outer spherical diameter of approx. 20 m a boil-off rate below 0.03 % per day can thus be achieved. This would allow a storage time over several years. Compared to compressed gas storage tanks, more favourable storage costs can be obtained for large hydrogen volumes.

The storage of liquid hydrogen in smaller stationary or transport tanks down to about 100 l is state of the art today similar to liquid helium. Larger tanks are in part also designed with perlite vacuum insulation, whereas smaller storage tanks are always provided with superinsulation and continuous exhaust gas cooling. Vacuum-superinsulated tanks attain boil-off rates in the range of 0.4 % per day, large tanks with vacuum powder insulation have losses of 1 - 2 % per day, depending on their geometry. Commonly used stationary tanks range from about 1,500 l contents (approx. 1,100 Nm^3) to 75,000 l (approx. 60,000 Nm^3).

Development aims above all at finding low-cost insulation materials and production methods.

Mobile storage

Small mobile storage tanks have been developed in Germany in connection with the activities for hydrogen vehicles. At present, such tanks are available as single units for passenger cars (installed in BMW test vehicles) and for buses (installed in the MAN-BUS SL 202), the bus tank consisting of three identical single tanks with elliptical cross-section holding 190 l each (this corresponds to an energy content of 450 kWh or 150 Nm^3. Energy densities of 4.5 kWh/kg or 2.13 kWh/l are achieved. The tanks consist of up to 200 - 300 layers of thin insulating foils (multilayer insulation, MLI), with which boil-off rates around 1 % per day are achieved. The evaporating liquid hydrogen leads to a pressure increase in the tank until the safety valve opens. The so-called "hold time", i.e. the time until the safety valve opens, is typically between three and five days for vehicle tanks.

2.2.4 Hydride systems and storage in new materials

Another method of hydrogen storage is to chemically store hydrogen with the aid of special metal alloys which form a hydride. In metal alloys up to 1.8 wt% of hydrogen can currently be stored, which corresponds to a storage density of about 0.6 kWh/kg. The high expenditure on casings and other devices for pressure and temperature control, however, significantly reduces the attainable storage density of the overall system by up to 50 %.

Starting from a high-temperature hydride, new materials for the reversible storage of hydrogen at temperatures below 200 °C are developed by alloying other components and forming nanocrystalline structures. Additional improvements are to be achieved by applying lightweight materials for the cylinder casing, so that a storage density of at least 0.7 kWh/kg or 2.5 kWh/l becomes possible.

An essential disadvantage of this storage technology is the low gravimetric storage density attainable. An advantage of hydride storage is that the storage process does not involve any losses. Energy is only required for temperature control in case heat has to be supplied for discharging. These losses can be reduced by interim storage of the heat produced during charging or by utilizing dissipated heat (for example engine waste heat) for discharging the storage cylinder.

Hydride storage systems have been developed for both stationary applications and for use as vehicle tanks as well as for the energy supply of portable electronic devices. However, the gravimetric storage density is clearly below that of liquid hydrogen, as is favoured for passenger car application, so that the opportunities of metal hydride systems for mobile applications, apart from niche applications (e.g. fork-lift trucks) are currently regarded as rather small. A very wide field of application for this storage technology could be in portable devices, since the high volumetric storage density and the safety of metal hydride systems are of great advantage here.

Another promising technology for storing hydrogen is the use of nano-patterned structures of graphite. Even if the values published for the storage density achieved have not always stood up to critical examination and the mechanisms of hydrogen intercalation are not yet clarified, there is the possibility that technically interesting storage capacities may be reached.

Current research activities are concerned with the search for suitable metals and alloys, and experiments are performed with different geometrical arrangements of the structures. The aim is to achieve a high storage density at pressures and temperatures close to normal ambient conditions.

Moreover, a large number of other materials such as sodium borohydride, microspheres or conductive polymers (polyaniline, polypyrrole) are examined for their suitability for hydrogen storage. However, these are largely basic research activities as yet and an assessment of technical feasibility is not possible at present.

Table 2-2: Need for R&D in the field of H_2 logistics

	Technology	**Need for R&D**	
Gaseous hydrogen	on-site production	• on-site reformer	cost reduction and series production
	long-distance pipeline transport		
	grid distribution	• cost optimization for municipal grids	
	pressure storage	• high-pressure systems (> 700 bar) • large storage tanks (~10,000 m^3) • materials	
	GH_2 filling station	• compressor (service life, costs) • high-pressure storage tank • optimization filling station integration and system design	
	hydride storage system	• storage capacity, low-temperature hydrides	
	advanced storage	• new storage concepts • materials	
	liquefaction	• efficiency optimization	
liquid hydrogen	LH_2 tank		
	long-distance shipping	• concepts	
	distribution by LH_2 truck	• reducing the filling losses	
	LH_2 filling station	• optimization filling station integration and system design • longer service life • reliquefaction • reducing boil-off	
Safety engineering	sensor technology and safety management		

2.3 Hydrogen applications

Hydrogen is a versatile energy carrier. A differentiation is made between the portable application of hydrogen in portable small devices, the mobile use in transport and traffic and the stationary application of hydrogen for domestic energy supply or in power plant technology.

2.3.1 Mobile applications

The use of hydrogen in the transport sector can basically take place in road traffic, air traffic, shipping and rail-bound transport. The driving force, however, is the use in the automobile sector for securing individual mobility beyond the age of oil and natural gas.

Traditional drive concepts based on the internal combustion engine have been continuously improved in past decades and it is to be assumed that the technology of present vehicle drives still has considerable potentials for reducing consumption and emissions and increasing performance and reliability.

In the sense of sustainable action it is necessary even today to look for alternative solutions for the drive system of the future. Apart from transferring the internal combustion engine principle to hydrogen as a fuel, the use of hydrogen in fuel cell systems with electric drives is currently being intensively advanced.

Common to both systems are the challenges of building up an infrastructure for the production and distribution of hydrogen at competitive costs and the issue of an optimum storage of hydrogen in vehicles. In addition, each system has specific advantages and drawbacks. In evaluating the technologies, in general, a differentiation has to be made between accomplished system properties and projected performance targets.

The most important distinguishing features of hydrogen combustion engines and fuel cell power trains are:

Efficiency:

Fuel cell vehicles even today achieve vehicle efficiencies of > 37 % in the NEDC (new European driving cycle; in the DaimlerChrysler F-Cell car (A class), for example, this corresponds to a diesel equivalent of 3.8 l/100 km) and have the potential for achieving 45 %. With these vehicle efficiencies, well-to-wheel efficiencies and CO_2 emissions comparable to present-day optimized diesel vehicles are achieved even if hydrogen produced from natural gas is used.

The efficiencies of vehicles with hydrogen-fuelled internal combustion engines are currently in the range of 26 % in the NEDC. For a reference vehicle of the VW-Golf class this corresponds to a consumption of 4.7 l/100 km diesel equivalent (3.9 l/100 km with additional hybrid system, EUCAR Well-To-Wheel Study). In the longer term, improvement potentials of up to 35 % (total system up to 50 % compared to 37 % today) are seen by BMW.

In future, moreover, a new type of hybrid is also conceivable: the combination of fuel cell and internal combustion engine. It will be the task of future research projects to analyse the potentials of this innovative approach.

Emissions:

Hydrogen-operated fuel cell vehicles are zero-emission vehicles. H_2-fuelled internal combustion engine vehicles are nearly emission-free, apart from very small quantities of NO_x.

Currently achieved state of the art and development times required:

Internal combustion engines with hydrogen as the fuel can be produced at about the cost level of diesel engines even today, with additional costs currently still to be accepted due to the bivalency, which will no longer be the case with a later monovalent design (with adequately available infrastructure). A hybridization of the H_2 combustion engine drive, which might be necessary for reasons of efficiency optimization, however, would increase vehicle production costs again. In the field of fuel cell systems with electric drives, in comparison, the prerequisites still have to be created for a market introduction within the next ten years.

Volumetric and gravimetric specific system parameters:

The specific performance data of present-day fuel cell systems are clearly below those of internal combustion engines. An adequate motorization of subcompact to compact vehicles (wheel power up to 80 kW) with fuel cell power trains is possible in the medium term. However, the technical goals are to be derived from practical system requirements. The latter must also be realistic, so that in the individual case the requirements ultimately predefined by the currently established technologies and consumer habits must be scrutinized.

Dependence on the density of the supply grid (tank range):

Due to the bivalency of present-day H_2 combustion engine drives, the density of the H_2 filling station network is less important here than for monovalent vehicles. However, the efficiency difference from fuel cell systems can only be reduced by monovalently designed H_2 combustion engines. For both systems, a sufficient density of the supply grid is therefore a basic prerequisite for market introduction.

Existing deviations between actual state and performance targets for efficiency, costs, service life, everyday suitability, functionability under all climatic conditions:

The theoretical potentials of fuels cells show clear efficiency advantages over the current state of internal combustion engine technology. With a view to the potentials of the other performance targets, however, possible interactions between the individual solution parameters must also be taken into account and optimized for different market and customer requirements.

Long-term potentials with a view to system parameters:

If it is possible to practically implement the theoretical prospects of fuel cell systems at competitive costs and if hydrogen from renewable sources can be increasingly made available, then this would be an important step towards a hydrogen-based transport economy. This would support the introduction of this drive variant in the lower vehicle classes. A possible expansion of the product range into the class of more powerful, larger vehicles as an alternative to the internal combustion engine essentially depends on the future improvement of the volumetric and gravimetric specific system parameters. Internal combustion engines fuelled with hydrogen from renewable sources for the upper vehicle classes are then also conceivable.

Production processes including required investments and costs of manufacture:

The known and cost-optimized production techniques for conventional internal combustion engines can be used for manufacturing H_2 combustion engines. Processes for the mass production of fuel cells still have to be developed, but considerable cost reduction potentials are seen due to the large number of identical parts.

2.3.1.1 Internal combustion engines

For the use of hydrogen in internal combustion engines, technical solutions with external (multi-point injection) and internal carburetion (direct injection) are to be distinguished.

The hydrogen combustion engine with external carburetion currently permits a power density approximately at the level of present-day gasoline engines. At the same time, the efficiency at low and medium load is above the level of present diesel engines. These potentials are realized with extremely low exhaust gas emissions below 1 % (HC, CO) and below 9 % (NO_x) of the emissions allowed according to EU4.

For cryogenic external carburetion, additional potentials for increasing the specific power by approx. 15 % are expected by cooling the intake air with hydrogen stored in the liquid form at -253 °C.

Internal carburetion also has the potential for higher power density, since air displacement in the cylinder is avoided due to the lower specific density of hydrogen fuel. Gaseous hydrogen is directly introduced into the combustion chamber during the compression phase. The concrete implementation of this concept will be embarked upon in the next generation of H_2 combustion engines around the year 2010.

The only relevant emissions from a hydrogen combustion engine are the nitrogen oxides arising at higher loads due to the high combustion temperature. A suitable operating strategy in combination with an exhaust treatment concept can also reduce these emissions to an insignificant level.

Operating strategies

- At low loads, hydrogen-air mixtures can be burnt in unthrottled homogeneous lean operation with NO_x emissions near zero. Low charge changing losses due to the unthrottled mode of operation and stable combustion provide a more favourable efficiency than for current diesel engines.
- At higher engine load, exhaust treatment by a conventional reducing catalyst reduces the NO_x emissions to near zero. This requires a stoichiometric operation (air/fuel ratio $\lambda = 1$) with load control by throttling the inlet air. External exhaust gas recirculation ensures the very good efficiency at the level of throttle-free lean operation.
- Above naturally aspired engine full load, a high power density along with NO_x reduction in the catalytic converter can be achieved by supercharging in stoichiometric operation.

Need for research and development in the field of H_2 combustion engines

- Provision of hydrogen in the vehicle at desired pressure and temperature
- Optimum design and function of the injector
- Optimization of the combustion process including the combustion chamber geometry
- Operating strategy for stoichiometric operation (air/fuel ratio $\lambda = 1$)

2.3.1.2 Fuel cell systems

Fuel cell systems provide electric energy with high efficiency and without toxic emissions. The only byproducts are waste air, water (vapour) and waste heat. The electric energy produced can be used in the vehicle for driving and/or operating electric consumers.

The most important advantage of fuel cell systems as power trains in comparison to internal combustion engines is the particularly high energy conversion efficiency in the part-load range, because most of the driving takes place in this power range (above all urban driving). A high efficiency is attractive here due to the resulting low fuel consumption of the vehicle.

In addition, the higher torque and more favourable torque band of electric motors in comparison to internal combustion engines with the same engine power leads to better acceleration values. An electric motor, moreover, does not need a multi-stage transmission and is comparatively quiet in operation. Both serves to increase the ride comfort.

Use for energy supply of the power train in a passenger car

For the propulsion of cars, fuel cell systems are generally developed on the basis of the PEM fuel cell. The following requirements or target values for fuel cell systems for vehicle drives can be derived from a comparison with available and future internal combustion engines:

Table 2-3: Requirements for fuel cell systems for car drives

Parameter	Value
net system power	60 – 120 kW (and more, if possible)
system efficiency FC (NEDC)	> 45 %
Power-to-weight ratio	< 3 kg/kW
service life	5,000 h over 10 years
cold-starting performance at -20 °C	< 15 sec
dynamics (idle up to 90 %)	< 1 sec
Costs	< 50 €/kW
Range	> 500 km

Additional decisive features are:

- low noise level
- ensuring comparable vehicle performance at high ambient temperatures
- good hill-climbing ability and
- good driving performance even at high altitudes (> 2,000 m)

In order to achieve these goals, significant progress must be made in comparison to the state of the art for the components of fuel cell drive systems:

Air supply system

- The air supply system must be more efficient especially at partial load and for greater air volumes at moderate pressure.

Humidification

- More efficient and, if possible, passive humidification technologies are needed for the anode and cathode, which can do without liquid water and can ensure minimum humidification.

Control systems

- For the control of FC systems, intelligent "thinking" control technologies are needed, which are capable of diagnosing the operating condition of the stack.

Stack technology

- Membranes are needed in which proton transport is largely independent of the water content. The membranes must be fully functional and long-term-stable over the entire temperature range from -25 °C to +140 °C with greatly fluctuating water content.
- Cold-starting performance of the system even at -25 °C within a few seconds.
- For the electrocatalysts, the stability (esp. CO tolerance) and activity must be significantly increased compared to the present state. For platinum-based catalysts, in

comparison to the state of the art, the platinum loading per unit area must be reduced by a factor of 3 and the power density per unit area improved by a factor of 2.

- On the whole, this means an improvement of the activity of the catalysts by a factor of 6. For non-noble-metal-containing catalysts, a similar improvement of the activity of the catalyst in the electrode is required.
- The service life of non-noble-metal-containing catalysts must be increased by a factor of 20.

The technical feasibility of fuel cell power trains in automobiles has been successfully demonstrated. In order to introduce this technology in series products, significant efforts are still necessary especially for the development of the base components.

Fuel cells for on-board power supply

The significantly rising number of electrical functions in vehicles requires constantly new strategies to satisfy the rising power requirements. If only for reasons of the continuously aimed at reduction fuel consumption, it is not purposeful to provide the required electric energy by using increasingly larger generators and batteries. Fuel cells as auxiliary power units (APUs) can take full effect here due to their system advantages, irrespective of the design (PEMFC for hydrogen, SOFC for conventional engine fuels).

Provision of electricity with higher efficiency

- In comparison to the conventional "engine - generator - battery" method, electric current is provided with higher efficiency due to electrochemical conversion. This contributes towards reducing fuel consumption and emissions.
- The modular design of a fuel cell enables optimum adaptation to future vehicle on-board systems with respect to voltage level and power.

Engine-independent operation

- Due to the fact that the operation of fuel cell APUs is decoupled from the drive engine, an energy supply of the vehicle is also possible with the engine switched off.
- This opens up options for new functionalities such as engine-independent air-conditioning or air heating. And precisely these extended functionalities with customer value could play a decisive role in the future market launch phase of fuel cell APUs.

2.3.1.3 Use of a fuel cell APU in aircraft

Power supply for passenger aircraft is effected today by a kerosene-fuelled turbine and involves high losses and emissions (noise, pollutant). In modern aircraft, electropneumatic and electrohydraulic components are increasingly used. The use of a fuel cell APU can efficiently, i.e. at lower operating costs, cover the thus increased power requirements and help fulfil future environmental protection requirements.

Since the use of hydrogen in air traffic constitutes a long-term option, kerosene will be used as the fuel in the first generations of fuel cell APUs for aircraft and processed into hydrogen by desulphurization, reforming and gas cleaning. Such systems are already being developed by the big aircraft manufacturers. Especially the desulphurization and reforming of kerosene have turned out to be the key technologies.

In comparison to stationary applications or to the automobile industry, the aeronautical industry makes the highest technical demands, but also offers the highest value-adding potential. Even if produced in small numbers, the application of fuel cell systems on board aeroplanes can contribute to the industrialization of fuel cell technology by synergy effects in other fields of application.

2.3.2 *Stationary applications*

Hydrogen technologies in stationary applications can meet future challenges of energy supply:

- integrating fluctuating electricity generation from renewable sources of energy
- maintaining grid stability
- rising demand for environmental protection and energy efficiency
- high investment demand due to necessary power plant renewal

Hydrogen basically provides the possibility of storing the fluctuating amounts of energy from renewable sources. However, the share of fluctuating power in the grid is continuously rising, so that the reserve capacity and regulating power required to ensure grid stability also increases. Intelligent systems of hydrogen production, hydrogen storage and use in gas turbines and fuel cells can contribute towards providing the energy from renewable sources fed into the electric grid with less temporal fluctuation while producing excess hydrogen as an energy carrier for e.g. applications in the transport sector.

Another field of application is emerging due the rising emission and efficiency requirements in connection with conventional electricity production. The combined generation of electricity and heat with low CO_2 emissions in decentralized fuel cells has a great market potential. This can be further increased if many small production units can be combined in virtual power plants to form a reliable and controllable system. Smaller decentralized units benefit from the fact that planning security with respect to fuel procurement and energy sales has decreased for investments in large power plants.

On the whole, it is true that for stationary energy supply in Germany roughly 40,000 MW – more than one third of the existing power plants – must be replaced within the next twenty years. If the development goals are reached in time, hydrogen technologies based on gas turbines and above all fuel cells will have a great market potential.

2.3.2.1 Turbomachines

Present-day electricity production is based almost exclusively on turbomachines with synchronous generators. They are characterized by high efficiency along with maximum reliability, long service life and low costs and as components of conventional thermal power plants form the basis for the economical use of electric energy. All technologies for electricity generation – except for niche markets – must therefore be measured against this technology.

Gas turbines are of great significance for the reduction of global CO_2 emissions. Intercooled 100 MW gas turbines with natural gas achieve efficiencies of up to about 40 %. Combined gas and steam power plants convert up to 60 % of the chemical energy into electric energy today. High dynamics and intervals of 25,000 operating hours between complete inspections are characteristic of turbines. Germany occupies a globally leading position in this technology. Power plant technologies with prior coal gasification under development use a hydrogen-rich fuel gas for the gas turbine, from the combustion gas of which CO_2 is to be separated and finally disposed of. Moreover, compressors and expansion turbines are required for the storage and transport of hydrogen.

Evolutionary and near-market development

- The reliability and service life of turbines for pure hydrogen are very likely to correspond to those of conventional turbines. As early as between 2008 and 2010 the first commercial systems can pave the way for the introduction of H_2 technology.

Development needs for H_2 turbines

- H_2 turbines need a burner that is designed for the extremely different ignition performance and higher flame velocity of hydrogen compared to natural gas while exhibiting low NO_x values.
- Optimization of the materials with a view to thermal stability at very high temperatures.
- Peripheral components require new materials; control and safety engineering must be adapted to hydrogen. Machine cooling has to be improved and the higher water vapour content in the combustion gas makes higher demands on the corrosion resistance of materials.

Future generations of gas turbines

- The next generation of H_2 turbines with higher inlet temperatures increases the efficiency by several percentage points. All developments will also be of benefit to turbine technology with conventional fuels. Approximately 10 billion euros must be expected for the conversion of present-day turbines up to 2010. The development costs for rendering H_2 turbines marketable by 2015 are one order of magnitude higher.

2.3.2.2 Fuel cell systems

The application of stationary fuel cell systems is characterized by the size of the systems used. In the power range < 50 kW, fuel cells are primarily used as CHP systems for the supply of buildings, whereas larger units are also applied by industrial customers. The fuel is generally natural gas, which is converted by reforming into hydrogen, carbon dioxide and small fractions of carbon monoxide.

For smaller systems, PEMFC or SOFC technology in the power class from 1 to 12 kW_{el} is currently being developed and field-tested. The target price of a complete system varies between 1,200 and 2,000 □/kW_{el}. Most of these systems require the input of heat, and a unit for covering peak loads or a buffer storage tank is additionally needed. The target value for the service life of the cell stack and essential plant components such as the reformer is above 40,000 operating hours and 15 years for the whole system.

The main goal of further technological development is to achieve marketability by reducing the costs. For this purpose, it will be necessary to reduce the complexity and dimensions of fuel cell systems. In addition, the integration in buildings must be simplified by interface optimization. Operational reliability must be increased and a long annual useful life achieved by higher flexibility of the fuel cell systems with respect to start-stop cycles, connection temperatures and power control.

In order to achieve these goals, the technical design of the fuel cell systems must be simplified. This requires further basic research for some components. In PEMFC technology, one focal point of development is to increase the operating temperature in the cell stack by a modified membrane. As a side effect, gas treatment and water management can be simplified and heat extraction facilitated. Another priority is the development of standardized components such as inverters, low-power proportioning pumps and suitable valves for humid reformate.

Fuel cell systems of larger design are being developed using MCFC, SOFC and PEMFC technology. MCFCs and SOFCs are characterized by high operating temperatures, so that they are suited for process steam generation typically throughout the year. Besides natural gas, fuels such as mine gas, sewage gas and biogas can be used. The required gas purities greatly vary between the fuel cell types.

The electrical efficiency should typically be above 40 % (MCFCs reach an electrical system efficiency of > 46 % today), and a fuel utilization totalling 80 % should be achieved. The target price of a commercial system is roughly 1,200 - 1,500 □/kW_{el} (including the costs for installation) and thus slightly above conventional combustion-engine CHP packages. A service life of 40,000 hours is regarded as the minimum requirement, after which it should be possible to continue operation after replacing the cell stack.

Development work is needed for the SOFC with respect to cell/stack technology and optimization of system integration also for hybrid systems, for the MCFC with respect to the operating means required and the start-up and shutdown performance, for PEMFC technology with respect to simple system design, electrical efficiency and water and temperature management. For all these systems, further research and development activities on cell stack technology are necessary to improve the production mode, operating temperature, start-up and shutdown performance and service life and above all the costs. It is extremely important to develop a manufacturing technology on a pilot scale for cells and systems to enable entry into the market. On the whole, the systems are as yet clearly too complex to achieve the target prices.

Reducing the complexity of fuel cell systems

- Reducing the dimensions of fuel cell systems by reducing the number of components
- Using standardized components from the subcontracting industry
- Higher operational reliability by a reduced number of components
- Increasing the operating temperature in the cell stack simplifies gas treatment, water management and heat extraction

Research and development for core components

- Cell stack development with the aim of reducing material input and increasing the service life
- Component development towards integrated and compact assemblies for e.g. fuel gas conditioning
- Build-up of manufacturing technologies for cell stack and gas treatment

Improving the operating results

- Increasing system efficiency by more efficient cells and reduced parasitic consumers
- Increasing the number of operating hours by reducing the error sources and by more flexible operating parameters
- Optimized system integration

2.3.2.3 Catalytic burner

Fuel cell systems generally do not use the fuel gases completely. The residual gases primarily consist of H_2 and methane in the case of using carbon-containing energy carriers. These gases must be burnt or catalytically converted and the arising process heat is generally used in the system. Furthermore, the burner units used in fuel cell systems must be rapidly startable, dynamic to operate, compact, powerful, reliable and inexpensive. In the last three decades, the development of catalytic combustion concepts has been pursued with particular intensity. Four different concepts for catalytic combustion are distinguished with respect to flow configuration and heat extraction (see Table 2-4). There are development potentials both in catalyst development and also essentially in reactor design.

Table 2-4: Concepts and data of different catalytic burners

		Flow configuration	
		covered by flow	**through-flow**
heat extraction	**convection**	**self-limiting catalytic burner** *- power density: 10 – 20 kW/*m^2 *- operating temperature: 120 – 250 °C*	**high-temperature catalytic burner** *- power density: > 1 MW/(bar* m^3*)* *- operating temperature: 800 – .500 °C*
	radiation	**diffusion burner** *- power density: 10 – 30 kW/*m^2 *- operating temperature: 330 – 500 °C*	**catalytic radiant burner** *- power density: 10 –120 kW/*m^2 *- operating temperature: 360 – 800 °C*

Catalyst development

- In catalytic total oxidation, methane combustion is characterized by unacceptably low volumetric performance and high kick-off temperatures of more than 330 °C. However, the nearly pollutant-free conversion of methane is indispensable for fuel cell use with reformer operation.
- The development of efficient catalysts for methane combustion with clearly higher volumetric performance is therefore of great significance. Whether the kick-off temperature can be lowered is questionable. Catalysts for hydrogen conversion are available.

Reactor development

- Reactors are so far designed on the basis of experience. Systematic procedures for reactor design based on kinetic data are to be developed. Design targets for the reactors are compactness, power density, reliability and economic efficiency. The power densities of currently 3.5 kW/l are to be increased to 10 kW/l.

2.3.3 Portable applications

Portable fuel cell applications can be divided into two areas: on the one hand, fuel cells replacing batteries in consumer electronics with power levels of up to approx. 50 W (laptops, telephone, video cameras etc), on the other hand, fuel cells for grid-independent power supply in the power range up to approx. 5 kW (e.g. emergency power, camping). For these applications, mainly hydrogen-operated polymer electrolyte membrane fuel cell (PEMFCs) and direct methanol fuel cells (DMFCs) can be used. The energy carrier is hydrogen or methanol. Methanol can be directly used in the DMFC or by reforming in H_2 PEMFC systems.

In the field of consumer electronics, the capacity and recharging time of the batteries is often a limiting factor for the applicability of portable devices. Mini and micro fuel cells can contribute towards overcoming these restrictions and ensure a long grid-independent useful life.

Depending on the application, the service life of fuel cells should be 1,000 - 5,000 h over a period of up to five years. These service lives are in part attainable with the technology available today. Thus, for example, service lives of several thousand hours were achieved in continuous operation for grid-independent power supply with fuel cell systems. The service life is thus in the range of conventional stand-by units based on combustion engines. However, the costs of manufacture are currently at least one order of magnitude higher than the selling prices of competing conventional units.

Another important criterion is the start-up time of the systems. At room temperature the H_2 fuel cells are operational within a few seconds. Maximum performance is provided after reaching the operating temperature, i.e. after a few minutes. Battery/fuel cell hybrid systems can ensure immediate availability of the devices.

The following factors play an important role in the field of portable fuel cell systems:

High customer benefit in the field of consumer electronics

- The power requirement of portable devices (consumer electronics) rises faster than the available capacity of storage batteries.
- Long grid-independent operation of the devices in arbitrary places is often only possible by fuel cell technology.
- Unlike storage batteries, fuel cells need no recharging time. The devices are operational immediately after and in part also during the replacement of the fuel cartridge.
- Unlike storage batteries there is no self-discharge in case of prolonged non-use. The devices are also immediately operational after long downtimes.

Short-term market introduction feasible

- The present technology permits market introduction in the near future.
- A cost level comparable to Li-ion batteries is feasible in the short term.
- A high and rising market volume in the field of consumer electronics enables rapid further development of the technology.
- Storage batteries can be replaced in wide areas. This reduces the volume of battery refuse with its heavy-metal problem.

High mobility and low environmental pollution by grid-independent power supply

- The use of hydrogen does not locally produce any harmful off-gases.
- In contrast to currently available conventional technologies (e.g. stand-by units based on combustion engines) there is no noise pollution.
- A use in nature reserves (e.g. water pollution control) is possible due to zero emissions.
- The units are largely maintenance-free due to the lack of mechanical components.
- Even the highest performance requirements in the military area can be fulfilled by this technology.

The need for R&D in the field of portable fuels cells is shown in Table 2-5: Future need for R&D in the field of portable fuel cells.

Table 2-5: Future need for R&D in the field of portable fuel cells

Development field	Need for R&D
fuel cell stack	• development and production of stacks in the range of 500 W, 1 kW and 2 kW based on "standardized" surfaces as a prerequisite for broad-based system development • development of portable PEMFC systems in the power range up to 1 kW • direct methanol systems for portable applications in the range of a few 100 W
cost reduction and efficiency increase	• development of catalyst materials with lower specific costs • new materials for the bipolar plates, which also permit mass production • development of new membrane materials • development of new sealing concepts and favourable sealing materials
improving the functionality and long-term stability of the individual components	• reducing the oxygen reduction losses • increasing the operating temperature of PEMFC stacks (for larger applications) • increasing the specific power in the room temperature range
modelling and simulation	• development of modelling and simulation tools for the FC systems and their components (dynamic and stationary) • development of system management strategies and control engineering models
peripheral components	• development of miniaturized components such as blowers, valves
fuel gas supply	• build-up of a fuel gas infrastructure as a prerequisite for the widespread use of fuel cells

2.4 Summary of research and development needs

2.4.1 Production

For a hydrogen energy economy H_2 is to be made available in large quantities and at the lowest possible costs. Hydrogen production will take place where low-cost renewable energy or other CO_2-free or CO_2-neutral energy systems are available. In Germany, for this reason, above all the development and fabrication of production and application technologies will take place. But the domestic resources (renewable energies or coal) must also be used for H_2 production. The task is to develop processes for low-cost and greenhouse-gas-neutral hydrogen production.

Currently, in Germany about 20 billion Nm^3 of hydrogen are provided annually. An increased use of hydrogen technologies requires a competitive expansion of the production and logistics capacities. Depending on the application technology, 35 to 40 billion Nm^3 of H_2 would have to be additionally provided to cover 10 % of the annual electricity consumption. In the transport sector 10 % of the energy content of all tanked fuels corresponds to 22 billion Nm^3 of hydrogen.

In order to lower the cost hurdles for the introduction of hydrogen technologies, low-CO_2 hydrogen production from natural gas is meaningful, especially if energy savings or reduced (local) pollutant emissions can be achieved by a high efficiency of the application technology. The steam reforming of natural gas has reached a technical level today which does not seem to urgently require enhanced research funding.

In contrast, the development of CO_2-neutral processes for the production of hydrogen should be increasingly intensified. This applies, in particular, to CO_2-free biomass gasification, coal gasification with CO_2 separation and storage, and the options described in the COORETEC report for CO_2-neutral power plants (to be downloaded from www.cooretec.de). A cooperation within the EU initiative HYPOGEN could be meaningful here, in which a large-scale facility for fossil-based hydrogen production with CO_2 sequestration is also to be demonstrated.

The development of small, decentralized reformers for the supply of portable applications, stationary fuel cells for domestic energy supply or for the provision of hydrogen at filling stations must be further advanced. There is above all a need for action concerning the exploration of low-cost catalyst materials and efficient systems. Electrolytic systems for local hydrogen production at filling stations must also be further developed. Especially for hydrogen filling stations, the overall system comprising production, storage and filling into the tank must be optimized by systems analysis.

There is a considerable need for funding concerning the development of processes for hydrogen production from renewable energy sources. The tasks range from basic research through application-oriented development up to demonstration projects (cf. also Table 5-1: Technology fields with high research priority). Electrolysis using electric current obtained from renewable energies is only one of the options and presupposes a (local) oversupply of the secondary energy carrier electricity. Other alternative methods such as photobiological or photochemical processes provide a great potential for low-cost hydrogen production, but still require considerable research efforts.

Even if hydrogen is initially produced from fossil energy carriers involving CO_2 emissions, the transition to CO_2-free hydrogen production from renewable sources or using other CO_2-free or CO_2-neutral technologies must remain ensured.

Within the framework of EU-wide CO_2 emissions trading, a suitable means will be available to prevent suboptimal developments.

The technology evaluation and systems analyses of the different hydrogen production technologies and of whole hydrogen utilization pathways are necessary to identify the best technologies from an economic and ecological perspective and earmark funds for these technologies. By means of holistic balancing it is also possible to identify conflicting uses at an early stage, e.g. in the use of biomass, and avoid wrong developments.

The following concrete recommendations are made:

Even if a variety of processes for hydrogen production are feasible, it is recommended that one should concentrate on processes applicable in the short to medium term. They comprise:

- On-site electrolysis and on-site reformers
- Central production and use of new liquefaction techniques
- Short-term implementation: use of hydrogen as a byproduct from refineries or chemical plants
- In the medium term, processes for large-scale CO_2-free production must be further developed, also from the aspect of using domestic resources (coal with CO_2 sequestration, wind, biomass) on a technical scale from 2015 onwards
- Market introduction and R&D activities must have long-term, consistent prospects of ensuring reliable boundary conditions for industry
- Systems analysis of the greenhouse gas balance of a hydrogen economy with life cycle assessment is necessary to compare the process chains/processes
- Dynamic application efficiency and competition analysis (competing use of primary energy sources in the course of time, resulting benchmarking).

2.4.2 Logistics

Although the technological fundamentals for hydrogen logistics are largely known and have proved efficient in the industry for many years, there is a lack of components and experience for future widespread application in a hydrogen energy economy.

In particular, suitable technical facilities and the safety engineering for public hydrogen filling stations must be further developed and practically tested to enable safe hydrogen handling also by untrained lay people in the future.

In order to be able to store and transport liquid hydrogen as an economically meaningful option, the energy losses during liquefaction must be minimized.

The present hydrogen storage technologies for motor vehicles do not yet meet the requirements to be fulfilled with respect to range and integrability into the vehicle. For this reason, new storage technologies must be explored and the existing ones further developed to offer customers at least the vehicle properties they are used to. For this purpose, the development of new materials and the investigation of the properties of storage materials are necessary.

For a transition phase it may be meaningful to use mixtures of hydrogen and natural gas ("hythanes"). It must be clarified here whether the existing infrastructure and the currently used application technologies are suitable for hythanes or whether measures for adaptation must be taken. Furthermore, investigations are needed in which hydrogen pipeline systems for the supply of filling stations and other large consumers are analysed.

The following concrete recommendations are made:

- H_2 management at tank or cartridge filling stations
- Mobile tank or cartridge filling stations
- Experience from ongoing, also European (e.g. CUTE) and international, projects should be largely used
- At the beginning, market introduction should concentrate on a few clusters to ensure an optimum capacity utilization of the infrastructure, concentrate know-how and minimize risks (e.g. by the redundancy of filling stations)
- Market introduction must be accompanied by supportive regulations, training and acceptance creation
- Drawing up a hydrogen roadmap for Germany embedded in a European context should be one of the next steps

2.4.3 Application

The large number of existing technologies for hydrogen use must be further improved and optimized for everyday usage. For the use of hydrogen in gas turbines, for example, suitable burners must be designed and materials for the turbine blades explored. Catalytic burners for fuel gas conditioning and conversion in the various application technologies must be optimized with respect to the properties of hydrogen and must ensure safe use.

In comparison to fuel cell technology, internal combustion engines enable an earlier use of hydrogen in transport and traffic, provided that the problem of H_2 storage can be rapidly solved. More efficient and environment-friendly private transport can be achieved by the use of optimized H_2 combustion engines still to be developed.

In the area of fuel cell technology, basic research is in part also required today for materials development. For mobile applications, the research and development of improved PEMFC stacks are given top priority. The aim here should be, in particular, to replace perfluorinated membranes by materials that are suitable for high operating temperatures and can be produced at low costs. Further examples are the development of platinum-free catalysts for the PEMFC as well as low-cost and long-lived electrolytes for the MCFC and SOFC. On the other hand, however, the development of manufacturing processes for all types of fuel cells should also be started in order to achieve the necessary cost reduction by mass production at an early stage. Up to the present, the competences for manufacturing fuel cell stacks, one of the most important components for H_2 application, are above all located outside Germany. Furthermore, components e.g. for air and fuel supply must be adapted to the fuel cell systems. For further necessary research tasks in the area of fuel cell technology, the strategy of the BERTA working group is referred to.

3 Legal framework conditions

3.1 Requirements for the introduction of hydrogen-based technologies

Hydrogen under ambient conditions is a gas and is stored, transported and processed in tanks and pipelines in the gaseous form under pressure, cryogenically liquefied or attached to metals. Experience has shown that a hydrogen economy can be safely controlled. But the safe handling of hydrogen requires specially adapted technologies and measures. In order to derive legal framework conditions from industrial experience, which permit a large-area application of these technologies, it is necessary to standardize technical regulations for the Europe- and worldwide licensing and registration of hydrogen technologies and to standardize components and subsystems, if possible, at an international level.

3.2 Status quo of national and international technical regulations

3.2.1 Stationary use of hydrogen

In stationary applications, hydrogen is mainly used today as a feedstock for the chemical industry. In this area, there are established registration and licensing procedures based on relevant legislation:

- Federal Immission Control Act
- requirements under construction law
- Operational Safety Ordinance

The situation is different for public energy supply, where hydrogen is not used at present.

Standardization and technical regulations in the gas supply industry

The German gas industry's special concern has always been a high safety level of the gas grids. Comprehensive technical rules have been established by the DVGW (German Association for Gas and Water). The technical rules contain requirements for a safe operation of grids and applications. They are anchored in the Energy Management Act and are permanently further developed. The gas supply industry thus also has comprehensive experience in the production, distribution and use of hydrogen-rich gases (e.g. town gas). This experience should be used for a possible application of hydrogen in the energy supply sector.

DVGW has published approx. 830 technical rules to date. They comprise the whole range of gas supply:

- gas transport and storage
- gas distribution
- gas pressure regulation
- gas measurement
- gas use (domestic, commercial and industrial)

Standardization has increasingly taken place at the European level for roughly ten years now. The relevant structures have been created by CEN, the European Committee for Standardization. The coordination of the European standardization projects in the gas sector is ensured by the "CEN Sector Forum Gas" under German leadership.

The legal basis of these projects is mostly embodied in European directives such as e.g. the Gas Appliances Directive (90/396/EEC). This directive contains technical requirements for "appliances burning gaseous fuels", and thus also hydrogen. The aim is to obtain a CE mark as a confirmation of conformity with the requirements of the directive. In Germany, this directive has been implemented in applicable law by the Appliances Safety Act.

There are a variety of current standardization projects in the European area (CEN), e.g. for gas space heaters, gas burners, gas meters etc. International ISO standardization bodies are concerned with gas conditions, hydrogen and fuel cells.

Town gas with high hydrogen content

Since the beginning of public gas supply in Germany in the middle of the 19th century, so-called town or long-distance gas has been produced and distributed for energy supply. Only in the course of increasing natural gas supply since the 1960s has town gas lost ground as a fuel gas.

Town gas mainly consists of carbon monoxide and hydrogen. According to the applicable technical rules, the hydrogen content of this technically produced gas is specified to be up to 67 % even today.

Strategic approach to hydrogen standardization

Natural gas is a possible bridging energy on the road to hydrogen. Standards and technical regulations for hydrogen should be based on existing structures and experience. Some hydrogen-specific requirements should be added. This essentially includes specific properties such as:

- wide ignition range with air
- deflagration and detonation behaviour (high laminar burn-off rate)
- corrosive behaviour towards some materials
- non-visible flame

But additional aspects must also be taken into consideration. They first of all include the reliable detection of possible hydrogen escape e.g. in the case of leakages. An odorous substance with a characteristic warning odour is admixed to natural gas. A corresponding alert system must also be installed for hydrogen.

Furthermore, the comparatively low heating value (roughly 1/3 of that of natural gas) requires an adapted infrastructure. The pipeline system with its technical devices (e.g. compressors, pressure regulation systems) must be modified accordingly. Another aspect results from the application of hydrogen: safe handling must be ensured for the customers (at present about 18 million gas customers).

Hydrogen standardization must be embedded in European standardization, since the legal basis for energy supply largely has its origin in European directives. Nevertheless, care should be taken that European standards are transferred into ISO and IEC standards wherever appropriate and required or ISO and IEC standards are reflected in CEN standards, in order to ensure the free cost-efficient and global exchange of components and products.

Registration of stationary applications

The licensing procedure for stationary systems including stationary devices for the hydrogen supply of vehicles, which takes several months, comprises the following steps:

- application for registration
- authority's response: a licence with detailed description of all requirements
- public hearing on the licensing document
- licence for the construction of the facilities
- inspection of the constructed facilities by public authorities/authorized body
- final licence for the facilities and operating licence.

Official licence, registration and certification:

- construction permit
- licence under environmental law
- operating licence
- CE certification with detailed documentation of the equipment
- document/certificate of acceptance by independent expert

The authorities normally involved in the licensing procedure are:

- environmental authority
- fire and explosion protection authority
- local building authority
- industrial safety authority

Important aspects concerning official licensing:

- applicable national regulations
- risk assessment (knowledge with respect to all safety-related parameters, operating and accident statistics is incomplete or lacking)
- CE marking (dependent of successful risk analysis, testing and operating experience)

ISO and IEC standards are needed for:

- units for H_2 production, handling and use – applicable: ISO/TC 197
- H_2 filling stations – applicable: ISO/TC 197
- H_2 filling connectors – applicable: ISO/TC 197 and subsumed ISO/TC 22
- fuel cells – applicable: IEC/TC 105
- H_2/FC units installed on board vehicles – applicable: ISO/TC 197, ISO/TC 22 and IEC/TC105

Proposal for the next steps:

Further extension of standardization-relevant know-how on hydrogen

- safety aspects at the customer
- materials

Creation of the basis for standardization

- screening the current technical rules for gas
- defining "delta" natural gas / hydrogen
- defining the standardization contents for hydrogen
- defining the structures at CEN (target: extension of ongoing projects, no additional projects)
- development-accompanying standardization
- international standardization at ISO and IEC level

Demonstration projects

- hydrogen addition to natural gas
- gaining operating experience with hydrogen and hydrogen-rich gases (e.g. use of chemical byproduct hydrogen in demonstrations for mobile and stationary applications)

Completion of standards

3.2.2 Registration and licensing of mobile applications

Road vehicles today only receive a Europe-wide type approval, as far as this is possible. This is done in applying the EU directives, which have to be implemented in national regulations by the member states.

The same procedure will also be applied to hydrogen vehicles. The overall type approval for a vehicle can be based either on system licences according to UNECE or alternatively on system licences according to EU directives (cf. Figure 3-1).

The European vehicle industry has decided to initiate a procedure for Europe-wide and globally harmonized hydrogen-relevant system licences for road vehicles within the framework of the UNECE WP29 UN organization. An advantage of this procedure is that due to the mechanism of the recognition of ECE regulations by the signatory states a national licence can be obtained more easily since it does not have to be issued separately for each member state. Moreover, the UNECE platform was chosen, since according to the 1998 agreement (E/ECE/TRANS/132 AND Corr.1) a globally harmonized licensing procedure for hydrogen road vehicles will be possible in future.

Since up to the present there are no Europe-wide technical regulations for hydrogen-specific components and subsystems of road vehicles (H_2 storage tanks, H_2 supply, H_2 safety components), establishing drafts for such technical regulations was already started in 1999 under the EU-supported EIHP project (European Integrated Hydrogen Project). These draft regulations and other hydrogen-relevant ECE regulations and EU directives (e.g. on crash behaviour, fuel consumption, vehicle emissions etc.) are established or adapted for the operation of hydrogen vehicles. Proposals for modifications were submitted for the areas of emissions, fuel tanks, fuel consumption, frontal crash, CO_2 labelling and electric vehicles, among others.

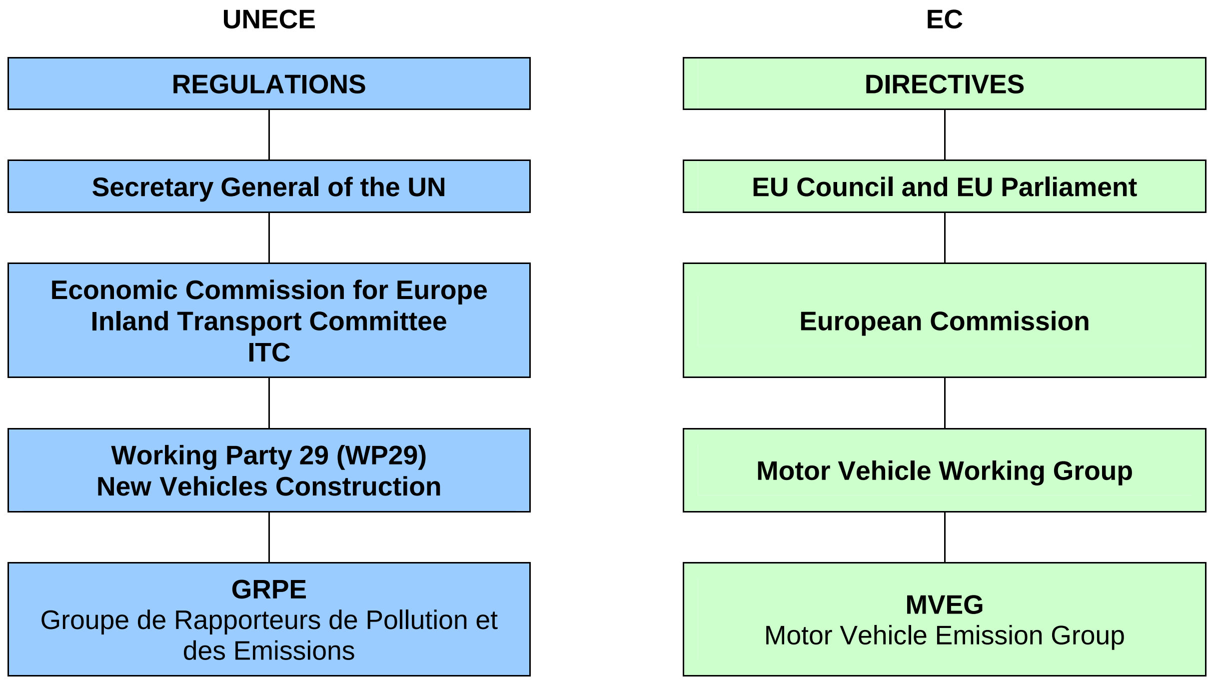

Figure 3-1: System licences for road vehicles

Moreover, the European industry is in agreement that a global harmonization of the licensing requirements within the framework of a global technical regulation (GTR) should be accomplished, in order to avoid different, costly vehicle developments for the largest markets of Europe, North America, Japan and China. A draft GTR would also be submitted to UNECE in Geneva.

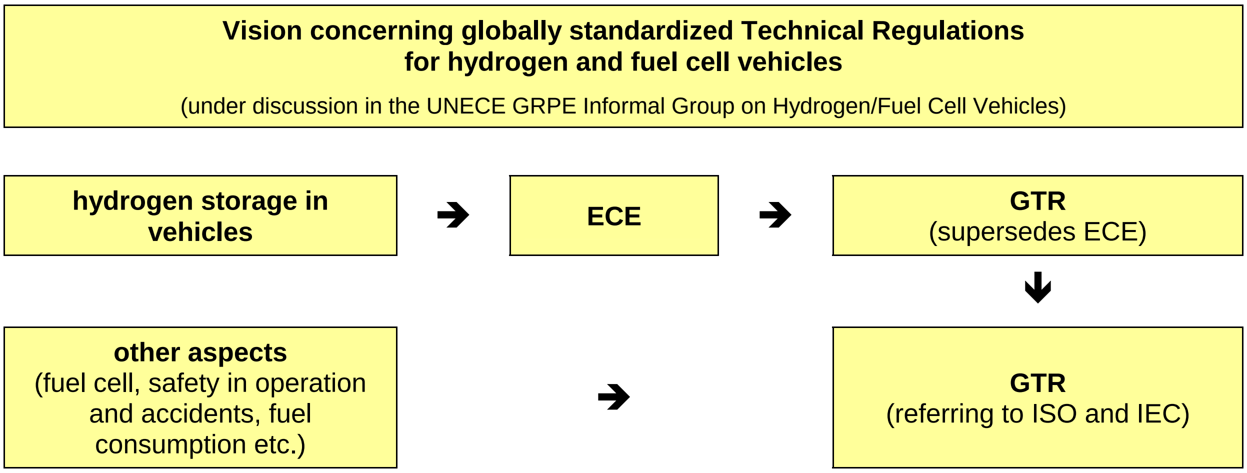

Figure 3-2: Pathways towards a global technical regulation (GTR) for H_2 and fuel cell vehicles

As far as this is possible, all hydrogen-relevant and engineered safety aspects should be incorporated in one (or several) GTR(s). The H_2 storage tanks and supply systems on board the vehicle (as to be provided for by the UNECE regulation) should be combined with the other safety-related topics such as fuel cell, safety under normal operating conditions, fuel consumption (i.e. the aspects already provided for in other UNECE regulations).

Hydrogen components for use on board a road vehicle and components for connecting the vehicle to stationary facilities, e.g. refuelling connectors at the filling station, but also facilities in the filling station itself, should be standardized via ISO (International Organization for Standardization), if possible, at an international level. Fuel-cell-specific aspects for mobile and stationary use should be standardized via IEC (International Electrotechnical Committee) at an international level.

The following technical committees are already concerned with the issues addressed:

- ISO/TC 197 – Hydrogen Technologies
- ISO/TC 22 – Road Vehicles
- ISO/TC 58 – Gas Cylinders
- ISO/TC 220 – Cryogenic Vessels
- IEC/TC 105 – Standards related to Fuel Cell Technologies
- UNECE/ WP29/ GRPE

3.2.3 Registration of portable applications

Metal hydride cylinders filled with hydrogen have so far not been allowed for transport by road or rail, or only with special permission, because they are not contained in the lists of the respective ordinances on hazardous substances. The Joint Meeting of ADR (Accord européen relatif au transport international des marchandises dangereuses par route; concerning the international carriage of dangerous goods by road) and RID (Règlement international concernant le transport des marchandises dangereuses par chemin de fer; by rail) decided on an amendment of the lists of substances in early October 2003. "Hydrogen in a metal hydride storage system" is now a dangerous substance of class 2 with the UN number 3468. All member states, including the states of the EU, must implement this regulation in national law. The new regulations will enter into force on 1 January 2005

3.3 Tax treatment of hydrogen

The tax treatment of hydrogen as an energy carrier is subject to the Mineral Oil Tax Law with the latest tax rates being valid since 01.01.2004[6] According to this law, hydrogen as a fuel is basically taxed at the rate for natural gas (13.90 €/MWh). It only remains tax-free if it is produced from biomass and thus fulfils the requirements of § 2a of the Mineral Oil Tax Law. In contrast, hydrogen used for heating, irrespective of its origin, is not subject to taxation within the meaning of the Mineral Oil Tax Law, since it does not contain hydrocarbons.

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[6] Mineral Oil Tax Law of 21.12.1992 (Federal Law Gazette I pp. 2150, 2185, 1993 I p. 169, 2000 I p. 147), as of 01.01.2004

4 Comparative evaluation of hydrogen energy technology

An evaluation of different hydrogen energy technologies on the basis of the results of the wiba perspective study "Technology and systems for hydrogen supply"[7] will be made in the following. For this purpose, the cumulative energy demand, the CO_2 emissions and the costs relative to 1 kWh H_2 at the place of use (final consumer) are balanced. The selection of the process chains results from meaningful combinations of individual processes at the levels of the energy carrier used, production and logistics. The current state of the art is compared to an estimation for the year 2025.

An evaluation of the use of hydrogen technologies is only possible by a comparison with conventional application technologies. For this purpose, the energy flows of both alternatives of a mobile, stationary and portable application are compared.

4.1 Evaluation criteria

Cumulative energy demand

The basis for balancing the cumulative energy demand (KEA) is VDI Guideline 4600 "Cumulative energy demand – terms, definitions, calculation methods". According to

$$KEA = KEA_H + KEA_N + KEA_E$$

the KEA can be calculated from the cumulative energy demands of production (KEA_H), use (KEA_N) and disposal (KEA_E) of the product. In this context, the material and primary energy demands for the individual stages of the process chain are to be balanced from the exploration of the base materials up to the disposal of the product.

Since the actual primary energy input must also be counted for renewable systems, the method of cumulative energy demand leads to comparatively poor results for renewable in comparison to conventional energy systems. The quality of the different energy carriers and technologies is lost in this approach. However, due to the separate balancing of renewable and non-renewable energy demands, an assessment of the different qualities of the individual technologies is possible. In the following, especially the non-renewable energy demand (KNRA) will be evaluated.

CO_2 emissions

With a view to the greenhouse gas reduction targets, the CO_2 emissions are balanced within the framework of the process chain analysis. On the basis of consumption quantities, lower heating value and fuel composition, the CO_2 emissions can be determined for solid, liquid and gaseous fuels. For electric energy production, the CO_2 emissions result from the weighted emission factors of the power plants used in the production mix.

Costs

For assessing the potential of new technologies, in particular, the current and future costs are decisive. In analogy to holistic energy balancing, first of all, the costs of the individual process steps are determined in the economic analysis. However, the data derived in /ANG 00/ are no longer fully reliable in all cases. The calculated costs are an estimate and should permit a classification and a comparison of the processes.

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[7] Angloher, J.; Dreiher, Th.: *Techniken und Systeme zur Wasserstoffbereitstellung, Perspektiven einer Wasserstoff-Energiewirtschaft Teil 1*, Koordinationsstelle der Wasserstoff-Initiative Bayern (wiba), Munich, 2000

4.2 Holistic evaluation of hydrogen supply

An evaluation of hydrogen supply must comprise all stages upstream of application. The systematics of process chain linkage is based on the energy balances of the individual processes. In process chains, the balances of the individual technologies chosen are linked with each other, so that all in- and outflowing energy streams are included. In the following, selected pathways of hydrogen supply will be balanced for stationary, portable and mobile applications. Depending on the time at which the pathways are considered, the technological and economic boundary conditions must be adapted (e.g. technological progress, cost degression due to mass production etc.).

4.2.1 Cumulative non-renewable energy demand

The choice of the primary energy carrier used and of the logistics has a significant influence on the KNRA per kWh of hydrogen supplied. In Figure 4-1 selected supply pathways for mobile, stationary and portable applications are shown.

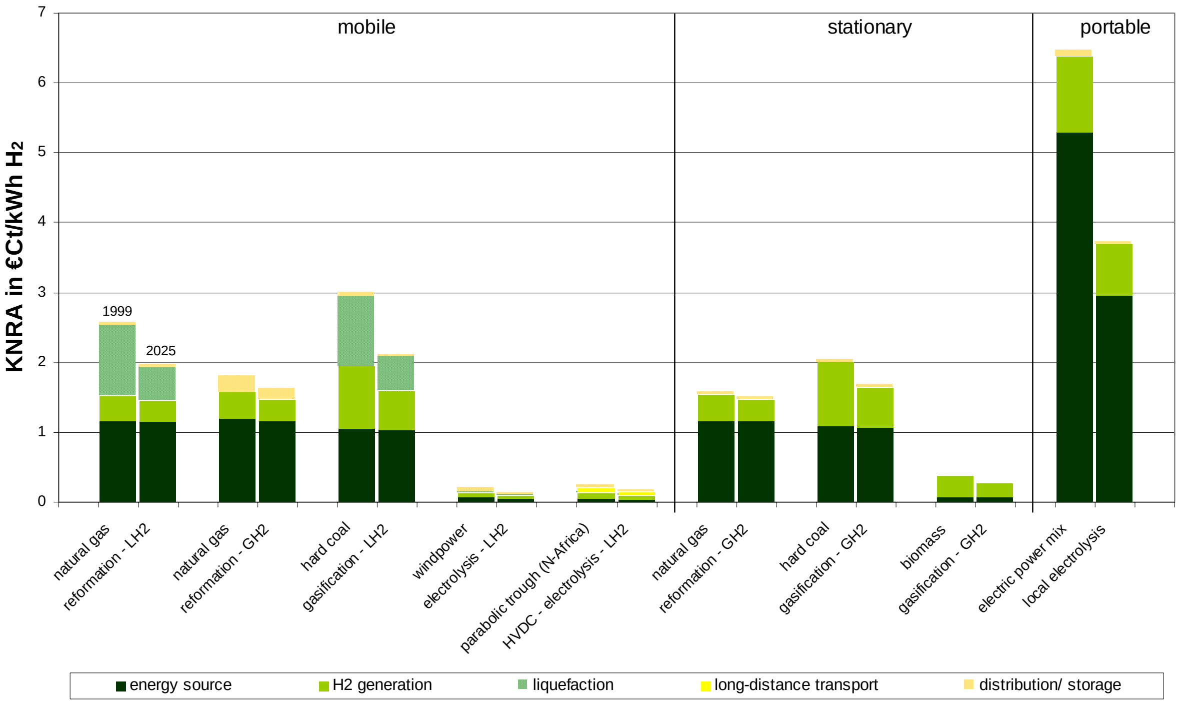

Figure 4-1: KNRA of selected H_2 supply pathways

Figure 4-1 shows that supply pathways based on renewable primary energy carriers exhibit clearly lower KNRAs than supply based on fossil fuels. The lowest KNRA is balanced for the production of hydrogen by electrolysis using electricity from wind power. From the energy point of view, the production of electricity in a parabolic trough power plant in North Africa is another alternative with low KNRA. Transport can be effected by high-voltage direct-current transmission (HVDC) or after electrolysis by pipeline (HG_2) or ship (LH_2). The steam reforming of natural gas exhibits the lowest KNRA for fossil energy carriers.

An important aspect of mobile hydrogen application is the technology of storage in the vehicle. Due to the required range, the use of liquid hydrogen is taken into consideration, but the use of pressure storage tanks may also be purposeful. The energy demands for liquefaction account for a significant portion of the KNRA. It should be noted here that in Figure 4-1 liquefaction in the renewable chains is effected corresponding to electricity from wind power and solar electricity, so that the KNRAs are clearly lower. In principle, the specific energy demands for liquefaction are independent of the supply pathway. This also enables a comparison of the alternative GH_2 supplies using the LH_2 pathways shown. The demands for distribution are higher for mobile than for stationary applications with otherwise identical pathway, since the supply via filling stations is clearly above that for distribution by a pipe system (cf. chain 1 and chain 6).

In stationary applications, fuel cells will probably be used primarily for combined electricity and heat generation. Thus, if electricity is to be the target product, pathways are excluded in which electricity is already available at a previous stage of the conversion chain, since that electricity could be better used directly and without further conversion losses. An exception is given if there is an asynchronism in time between electricity generation and electricity demand, as in the case of wind and solar electricity. Priority is thus first given to the thermal processes of hydrogen production from fossil sources, such as the provision from natural gas and coal. The application in stationary fuel cell systems does not require the high storage density needed for use in passenger cars, so that gaseous hydrogen is given preference in order to avoid the high liquefaction demands. On a large technical scale, the supply of fuel cell CHP packages can only be performed by pipeline, so that a pipe system similar to the natural gas grid is assumed for GH_2 distribution. An exception is the gasification of renewable raw materials as is balanced in the biomass chain. As expected, this renewable variant exhibits lower KNRAs than the fossil supply pathways. Among the fossil alternatives, natural gas steam reforming proves to be the most favourable variant in terms of energy.

The use of hydrogen for energy storage in portable devices is of minor significance for the energy sector. For hydrogen supply in portable devices, in principle, both a decentralized and a centralized supply structure is conceivable. If a fuel cell with H_2 storage is to be used like a storage battery, an electrolyser as a small device in analogy to the battery charger must produce the hydrogen, which is then fed in using a hydride storage unit. The electrolyser can be supplied from the general power supply or alternatively from a photovoltaic module. Another possibility is to charge the storage tank from a hydrogen pressure cylinder filled by a gas supplier. Hydrogen production is thus centralized involving additional expenditure for the distribution of pressure cylinders compared with more favourable production conditions in centralized large facilities. In Figure 4-1 decentralized electrolysis is balanced using the electricity mix. This supply pathway shows the high energy demands for the energy carrier and H_2 production due to the composition of the German electricity mix with a high share of thermal power plants.

Concepts for CO_2 separation and CO_2 storage were investigated in the COORETEC report[8]. The technology of gas scrubbing for CO_2 separation is thus known in principle. However, the availability and efficiency under power plant conditions still have to be demonstrated in pilot plants. In the case of appropriate technical availability, another supply pathway is thus the option of decentralized hydrogen production by electrolysis e.g. at filling stations using electricity from central power plants with CO_2 sequestration. It can be seen in Figure 4-1 that production from the electricity mix exhibits a very high KNRA. This ratio would even further deteriorate, since according to the COORETEC report efficiency losses of 6 to 14 percentage points arise, so that there will be an additional fuel demand of 10 to 35 % at the same nominal power. Added to this are demands for CO_2 transport and storage. These would also arise in the thermal processes for hydrogen production with corresponding CO_2 sequestration. Another possible concept for power plant processes with CO_2 sequestration is based on coal gasification with pre-combustion capture. The hydrogen thus produced could therefore also be used directly. Depending on the application, the demands for the downstream stages of hydrogen supply would correspond to those in Figure 4-1.

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[8] BMWA (ed.): Research and Development Concept for Zero-Emission Fossil-Fuelled Power Plants, 2003. To be downloaded from www.cooretec.de

4.2.2 CO_2 emissions

There is a close relationship between non-renewable energy input and associated CO_2 emissions (cf. Figure 4-2).

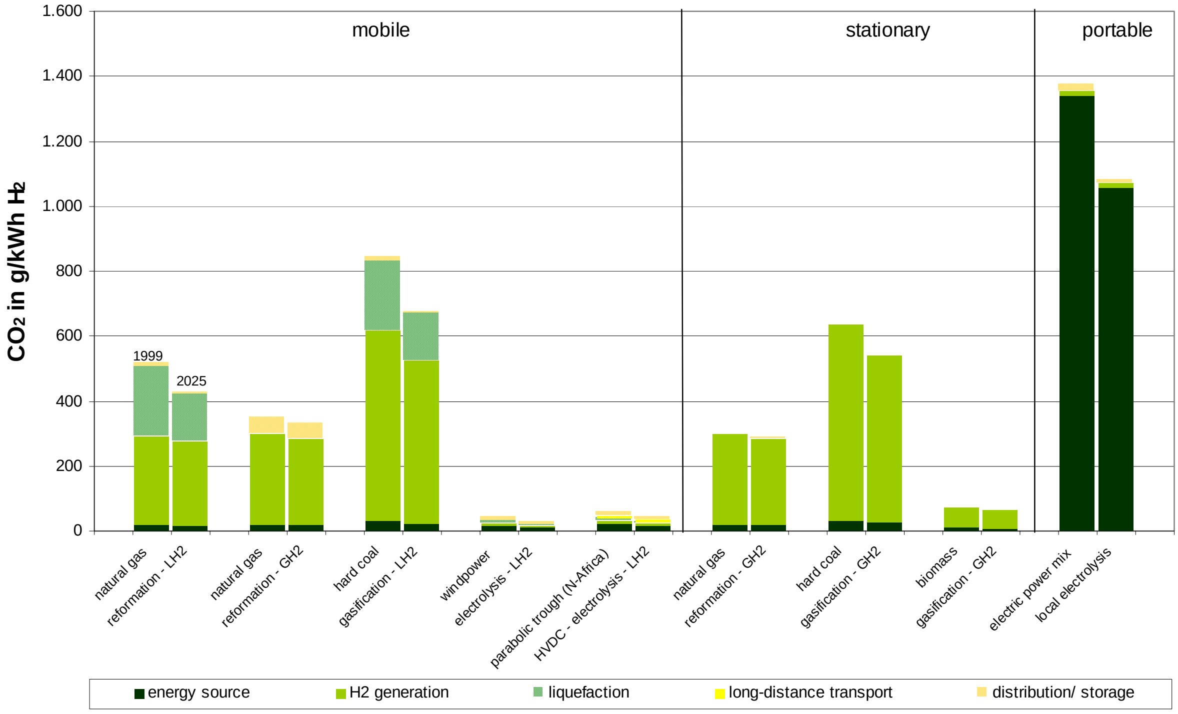

Figure 4-2: CO_2 emissions of selected H_2 supply pathways

As expected, the renewable pathways also come off clearly better concerning CO_2 emissions than the fossil variants. The differences within the fossil production variants are even greater in comparison to the KNRA, because in the steam reforming of natural gas a clearly better H/C ratio takes effect in addition to higher efficiencies. The carbon released as CO_2 during the gasification of biomass was bound during plant growth and is therefore rated as neutral. The CO_2 emissions identified arise in fuel conditioning, fuel transport and plant manufacturing.

Supply pathways with CO_2 sequestration would considerably improve the CO_2 balance, since only very low CO_2 emissions arise for energy carriers and H_2 production depending on the capture rate. For the downstream stages, however, corresponding CO_2 emissions would continue to arise.

4.2.3 Costs

In comparison to the KNRAs and the CO_2 emissions, a completely different picture is obtained for the costs in Figure 4-3.

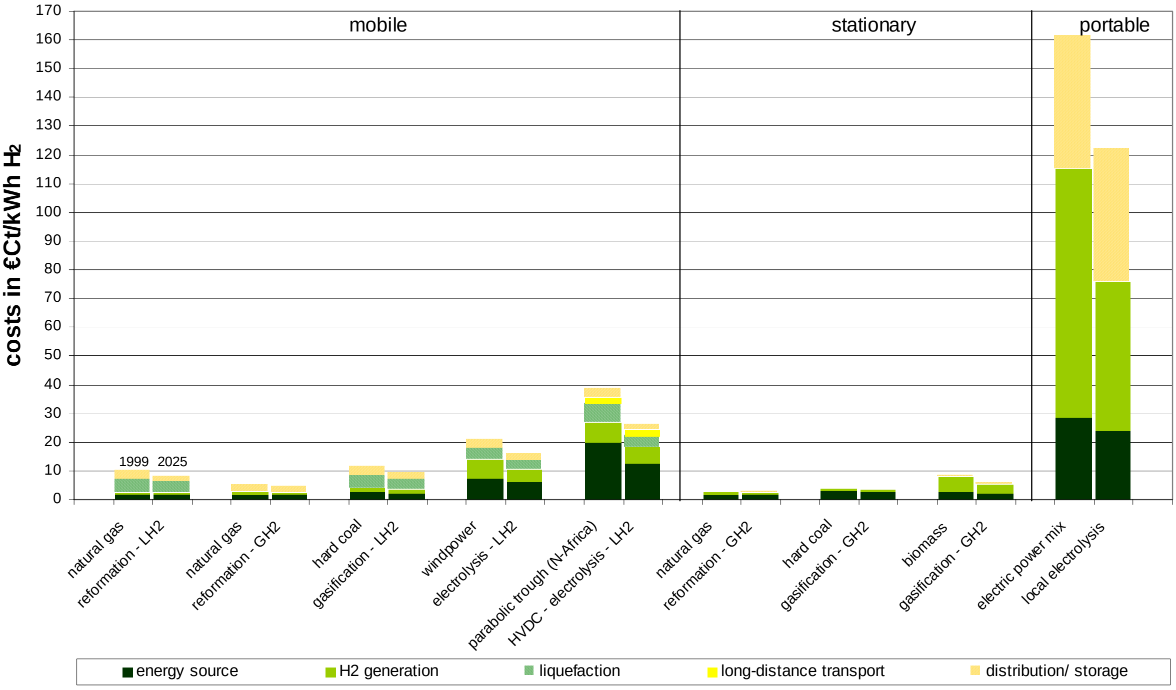

Figure 4-3: Costs of selected H_2 supply pathways

Clear advantages can be seen for the fossil supply pathways, which are below the solar variants by a factor of five to ten. Electrolysis with electricity from wind power is still about twice as high as the provision from natural gas steam reforming. Only the production of hydrogen from biomass will in future come into the cost range of fossil production. Centralized hydrogen supply for portable applications is about a factor of ten higher than a decentralized solution due to the high costs for distribution. But also for the decentralized alternatives, the specific costs are still clearly above those for mobile and stationary applications, since further costs arise for very small electrolysers and hydride storage units.

Supply pathways with CO_2 sequestration would considerably increase the costs. For power plants with capture processes, for example, additional investments of 30 to 150 % would be necessary. The additional costs for transport and storage in Germany would be another 10 to 24 □/t CO_2. Corresponding estimates are required for reforming and gasification processes.

4.3 Comparison of conventional technologies with hydrogen technologies

4.3.1 Comparison of passenger car propulsion technologies

In the wiba study "System comparison of alternative propulsion technologies"[9], two hydrogen-fuelled variants were also investigated within the framework of the primary energy analysis of the manufacture and use of propulsion technologies. Some of the results are shown in Figure 4-4.

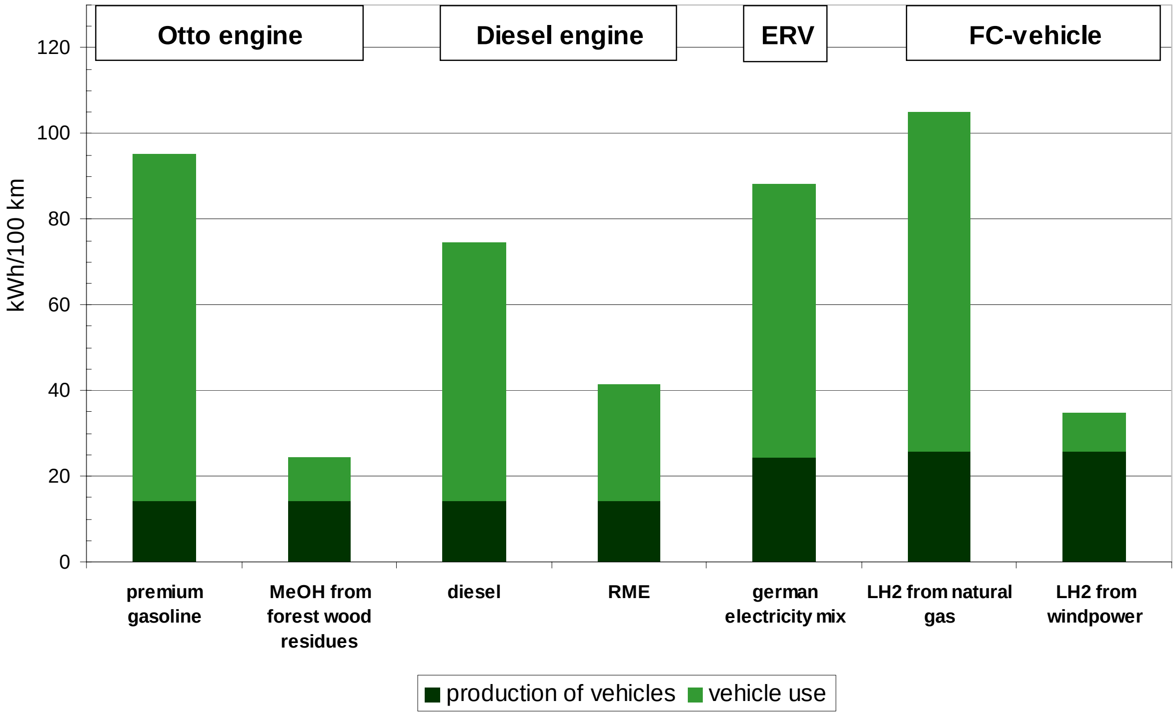

Figure 4-4: KNRA of different propulsion concepts over the life cycle

The use of hydrogen technologies in the transport and traffic sector may lead to a reduction of the KNRAs in addition to reducing local emissions. The demands for manufacturing the vehicle (especially for the fuel cell) are clearly higher for hydrogen-fuelled PEMFC vehicles than for vehicles with conventional internal combustion engines. Nevertheless, due to the comparatively high efficiency of the fuel cell, lower KNRAs per distance covered can be balanced over the entire life cycle. For the energy balance, the underlying supply pathway for hydrogen is decisive. In the balancing of vehicle use shown in Figure 4-4, however, the demands for vehicle maintenance and for the infrastructure are not included. For the energy balance of mobile hydrogen applications, the underlying supply pathway is decisive.

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[9] Corradini, R.; Krimmer, A.: *Systemvergleich alternativer Antriebstechnologien – Primärenergetische Analyse der Herstellung und Nutzung alternativer Antriebstechnologien im Vergleich zu konventionellen Systemen für den PKW-Bereich, Perspektiven einer Wasserstoff-Energiewirtschaft Teil 4*, Koordinationsstelle der Wasserstoff-Initiative Bayern (wiba), Munich, 2003

4.3.2 Example of stationary application

One possible application of hydrogen technologies is domestic energy supply. In the wiba study "The Virtual Fuel Cell Power Plant"[10], the electricity and heat supply of a settlement with fuel cells was compared to a conventional supply system. The comparison of the energy flows is shown in Figure 4-5 and Figure 4-6.

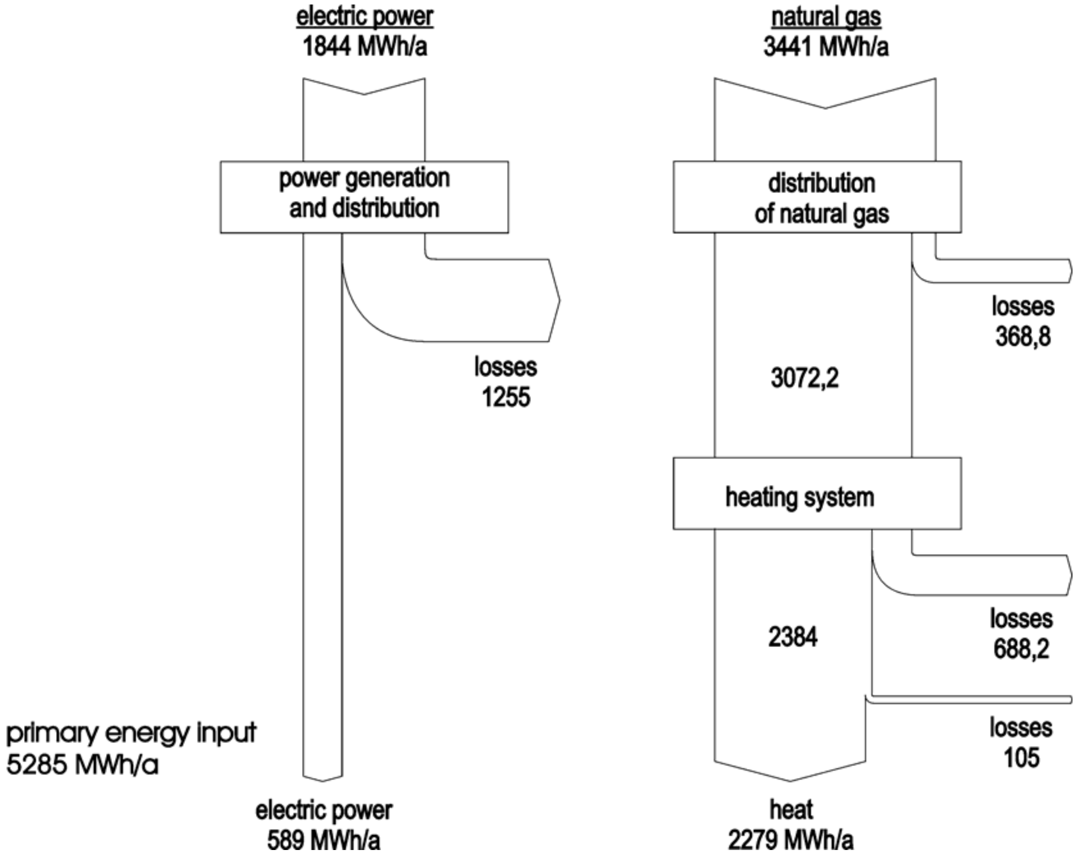

Figure 4-5: Conventional electricity and heat demand coverage of a settlement (existing)

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[10] Arndt, U.; Köhler, D.; Krammer, T.; Mühlbacher, H.: *Techniken und Systeme zur Wasserstoffbereitstellung, Perspektiven einer Wasserstoff-Energiewirtschaft Teil 3*, Koordinationsstelle der Wasserstoff-Initiative Bayern (wiba), Munich, 2002

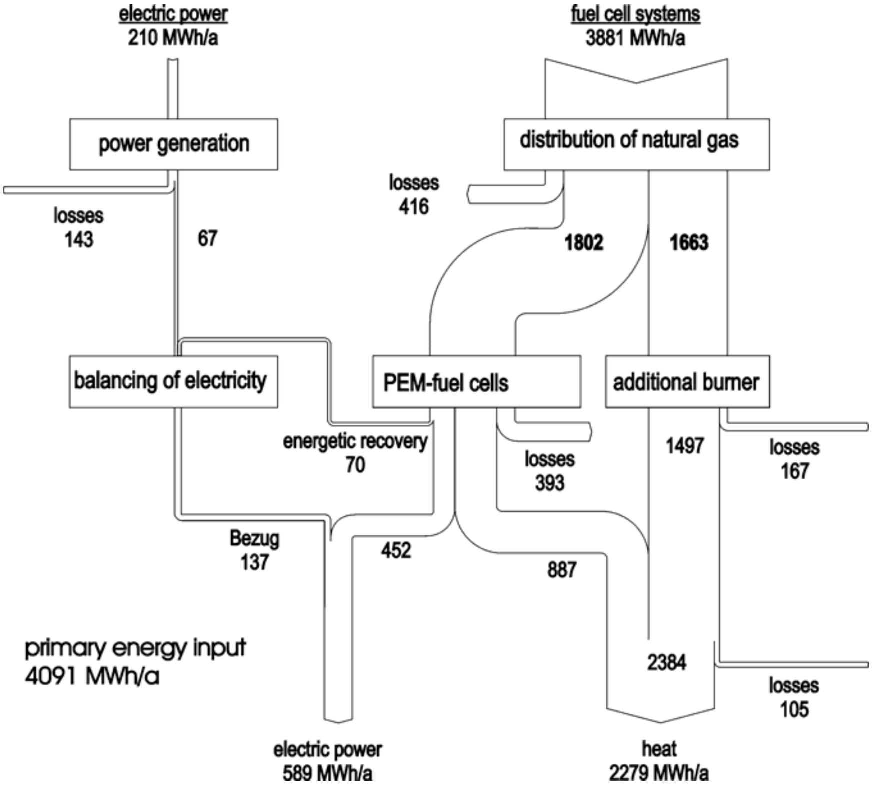

Figure 4-6: Electricity and heat demand coverage of a settlement with electricity-based PEM fuel cell system

The comparison of the alternatives for domestic energy supply shows that decentralized electricity production by PEM fuel cells can lead to savings in primary energy input. However, the shown savings of 23 % compared to conventional electricity and heat supply are only achieved, if the expected efficiencies and operating times of the PEM fuel cells are attained. If instead of the utilization rates for existing technologies a reference variant with heat recovery boiler and gas and steam turbine power plant is assumed, nearly the same primary energy consumption results in comparison to fuel cells. In the variant shown in Figure 4-6, hydrogen is produced in a decentralized manner from natural gas by a reformer integrated into the fuel cell system. The efficiency of the fuel cell system would increase in the case of using hydrogen, but the choice of hydrogen supply is also in this case decisive for the overall energy balance. The use of renewable energy carriers for the production of hydrogen in combination with fuel cells for domestic energy supply could lead to a clear reduction of the KNRA.

4.3.3 Example of portable application

The technology evaluation and potentials of fuel cell systems for small portable devices were evolved in/ARN 03/[11]. An energy supply system for notebooks based on Li-ion batteries was compared with a PEM fuel cell system. The provision of electric energy was balanced for the conventional alternative with the process chain German electricity mix – battery charger – Li-ion battery and for the hydrogen-based alternative with the chain natural gas steam reforming – compressed gas cylinders – metal hydride storage – PEM fuel cell (cf. Figure 4-7).

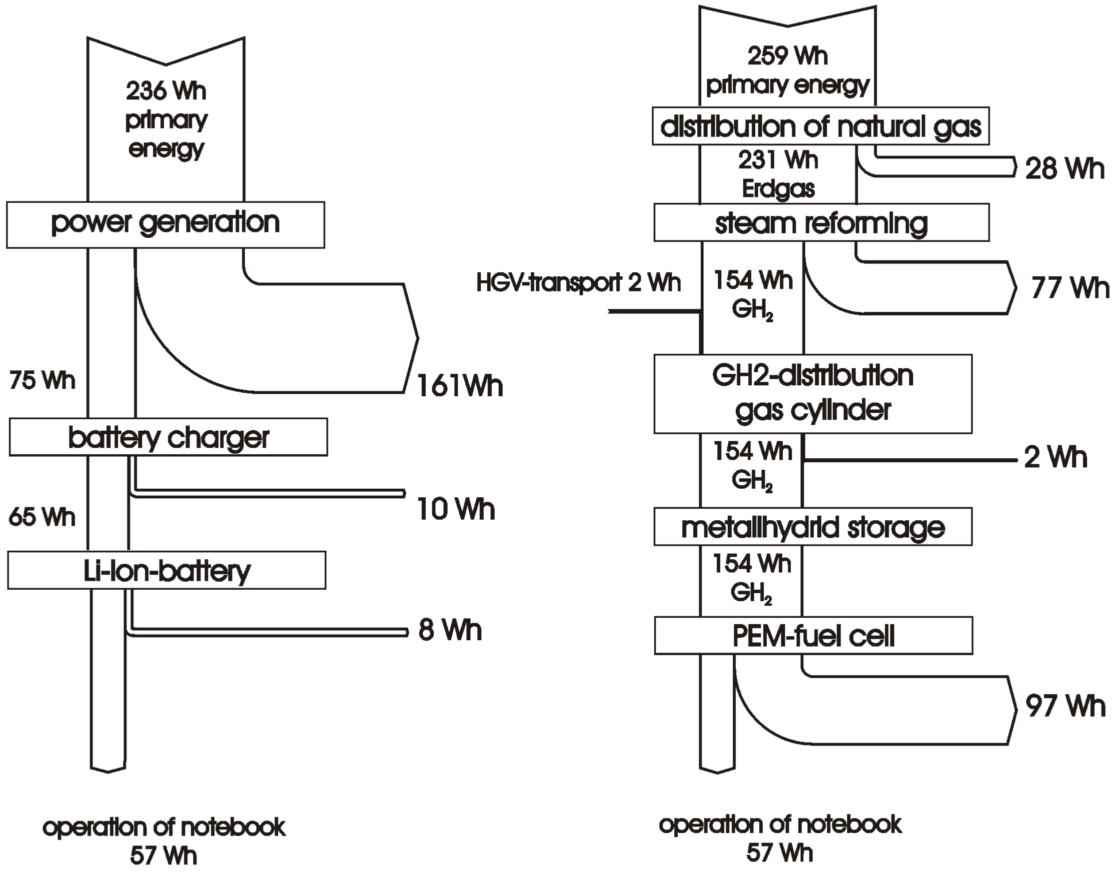

Figure 4-7: Energy flow charts of a notebook with Li-ion battery and a notebook with PEM fuel cell supply

The fuel cell variant has a KEA of 4.54 kWh/kWh$_{el}$ compared to 4.14 kWh/kWh$_{el}$ of the Li-ion battery variant and thus an additional energy demand of about 10 %. With an electrical efficiency of 37 % on average, the PEMFC system cannot compensate the losses of natural gas reforming. However, the relevance of portable small devices in terms of energy is small. Market opportunities for hydrogen technologies in portable applications arise due to the higher gravimetric and volumetric energy density of energy storage in comparison to battery technologies and the longer running times thus attainable.

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[11] Arndt, U.; Hauptmann, F.; Kraus, D.; Richter, S.: *Brennstoffzellensysteme für portable und stationäre Kleingeräte – Technikbewertung und Potenziale*, Forschungsstelle für Energiewirtschaft e.V., Munich, 2003

5 Recommendations by the Strategy Group

The build-up of an energy system using hydrogen technology requires a long-term research and implementation strategy, which is capable of coping with the risks of establishing development steps for the public sector, on the one hand, and for industrial organizations and investors, on the other. A broad-based introduction of hydrogen technologies requires very high investments in production capacities, in the infrastructure and the diverse applications, which cannot be borne by individual businesses alone. Cooperations can moreover help to reduce the risks of low efficiency still existing today for some hydrogen technologies.

The driving forces for the market launch of hydrogen are the security of energy supply, air quality and health protection as well as global climate protection, and they are thus essentially of a political and social nature and do not represent any direct incentives for economic action. Only with clear political signals and thereof resulting economic incentives for hydrogen-based applications will market participants substantially share in these development costs. With these measures it is also possible to strengthen the industry's competitiveness on an international scale. Public funds for research developments and their introduction on the market are therefore indispensable. It is also important here that other policy fields such as the environment and taxation are consistent with technology funding.

5.1 Updating funding policy in the field of hydrogen technology

In order to maintain the actors in research, development and industry for hydrogen technology and know-how in Germany and to attract new actors, long-term and continuing policy support and financial support is required from the Federal and state governments. To this end, the Federal Government's funding policy in the field of hydrogen and fuel cell technology is to be updated. Fuel cell technology, which is given major priority today, must continue to be funded at least to the present extent. The variety of the fuels to be used also enables the breakthrough of fuel cells even without hydrogen. On the other hand, hydrogen can also become an important component of future energy supply without the fuel cell. Research and development in the field of hydrogen technology must therefore tie into the efforts and successes of the 1990s.

Along with clear political signals and economic incentives, the pioneers in the development of hydrogen technology and in laying the first foundations for a hydrogen infrastructure must be supported. In the long run, it will thus be possible to win private business over to the required significant investments in a hydrogen energy economy.

The aim of this policy must be to speed up the most important research activities and technical developments in Germany. Only in this way can the necessary know-how be obtained for a pioneering role in the introduction of a hydrogen energy economy and for maintaining the German industry's competitiveness by the export of products and services.

5.2 Recommended priorities in R&D funding

In order to utilize the advantages of hydrogen energy technology and make this technology economically competitive, continuous long-term funding is required, which must comprise research and development projects as well as demonstration projects and future support for market introduction.

In general, there must not be any politically motivated preferences for individual technologies, and the decision on the use of specific technologies (e.g. storage in liquid or gaseous form, car propulsion by means of fuel cells or internal combustion engines) must be made by the market or the user.

The individual hydrogen technologies are at very different development levels. While basic research is in part required above all on new materials, there are technologies and applications close to market entry. This inhomogeneity can be dealt with by suitable funding strategies and funding can be adapted in the different technology fields in such a way that none of the areas of production, logistics or application will become a bottleneck in an emerging hydrogen energy economy. The major funding priorities discussed in the Strategy Group are compiled in Table 5-1: Technology fields with high research priority.

One of the first steps towards coordinated and long-term funding of hydrogen energy technology should be to define a hydrogen strategy for Germany (National Hydrogen Energy Roadmap). Embedded in the European and international context, the research priorities for the next few years must be shown, a strategy developed for building up a hydrogen infrastructure and approaches for the market introduction of application technologies described.

Two important general research priorities are already discernible at present:

- CO_2-neutral production of hydrogen and
- hydrogen storage for mobile and portable applications.

In supplementation, research funding in the application technologies would also be important. There is an urgent need for action in this area, too, in order to develop suitable technical solutions and enable the breakthrough of hydrogen applications on the free market.

Table 5-1: Technology fields with high research priority

		Funding Areas			
		systems analysis	**basic research**	**application-oriented R&D**	**demonstration projects**
Technology Area	**production**	holistic technology evaluation esp. conflicting uses	alternative H_2 production technologies catalyst technology for decentralized reformers CO_2 separation and storage for gasification technologies	HP electrolysis H_2 from gasification technologies, e.g. from coal or biomass H_2 from (offshore) wind energy system issues concerning decentralized reformers (for filling stations, stationary and portable applications) H_2-permeable membranes gas conditioning/cleaning	national large-scale projects and EU lighthouse projects e.g. H_2 rail South Germany, Hamburg city port
	Logistics		gas separation (H_2 and CO_2) new storage technologies	high-efficiency liquefaction plants GH_2 and LH_2 storage filling station components, pipeline systems and hythanes safety technology	
	application		materials development for PEM, MCFC and SOFC materials development for HP H_2 turbines	H_2 combustion engine H_2 burner for gas turbines catalytic burners membrane fabrication FC fabrication peripheral components for FC and H_2 applications	

5.3 Demonstration projects

Large-scale demonstration projects (e.g. EU-wide Lighthouse Projects), in which the production, distribution and infrastructure for hydrogen are tested together with applications, provide German developers and manufacturers with the possibility of testing their technologies and comparing them on an international scale. The practical experience gained in such projects concerning everyday suitability and the interplay of the individual components is an important part of technology development, and the companies involved will thus obtain a significant knowledge lead. The findings can also be presented to international bodies for standardization.

Political and financial support for EU Lighthouse Projects and national pilot projects (e.g. H_2 motorway) is necessary in order to encourage internationally acting large companies and also small and medium-sized enterprises to become engaged. In future, regions with hydrogen demonstration projects and suitable infrastructure can be the cradles of a hydrogen energy economy.

5.4 Legislation and standardization

Present legislation on the use of hydrogen is not suited for an everyday hydrogen energy economy. Thus, the high costs of H_2 installations (e.g. filling stations) are in part also due to the fact that the required licensing procedures involve very much time and work.

For this reason, it is necessary to create a practically suitable and uniform legal basis for the production, logistics and application of hydrogen. It is not necessary here to create new regulations in all areas, but it is often sufficient to adapt existing regulations and facilitate their application, e.g. by reducing the institutions involved in licensing. European directives that can be speedily and in an identical way implemented in national law are desirable.

Internationally defined laws and regulations will accelerate a joint development and market introduction of hydrogen technology. The creation and implementation of such directives must proceed speedily, so that they do not constitute an obstacle but serve as an aid and enable planning security.

Standards agreed upon by the industry will facilitate and accelerate the market penetration of hydrogen technology. Firming up these standards is the task of the companies involved, the creation of suitable legal and political boundary conditions must be ensured by state authorities.

5.5 Interfaces with international activities

Cooperations at the European and international level such as the EU H_2/FC TP and the IPHE are required to accelerate development by an exchange of know-how, measure basic know-how on a global scale and derive methods for the internationally necessary standardization of base technologies.

Both the European H_2/FC TP and the international IPHE were only instituted with great political support in late 2003. The bodies of both initiatives only met a few times and there remains enough room for the German delegates to put life into these initiatives by coordinated proposals and project ideas and ensure added value for Germany. A coordination of all these activities is necessary to increase the efficiency of work and the value of the R&D efforts and to avoid double handling.

The German commitment in the European and international activities will only bring the desired added value if these activities are coordinated and combined at the national level, in order to create targeted possibilities of information exchange with German enterprises, scientific institutions and the federal and state ministries involved. The BMWA Strategy Group forms an excellent platform here, because in addition to the hydrogen actors the fuel cell experts of the BERTA working party are involved, too, as are the representatives of the federal states with ongoing programmes in the field of fuel cells and hydrogen.

5.6 The future of the Strategy Group

The H_2 Strategy Group has completed its first task by drawing up this report on the technological hydrogen strategy.

It was suggested, however, that a joint HYBERT advisory council should be created from the H_2 Strategy Group and the BERTA working party which should develop recommendations to the federal ministries. Furthermore, this council should develop a strategy for the German role in European and international cooperation and facilitate national cooperation between federal ministries as well as federal states, industry and research.

For the above tasks, structures may have to be built up ranging from information procurement and processing up to information dissemination, and the management of such an advisory council should be transparent, independent and effective. In this connection, the creation of a "Hydrogen and Fuel Cell Coordination Office", which is currently being envisaged, is basically advocated by the Strategy Group.

6 Annex

6.1 The participants of the Hydrogen Strategy Group at BMWA

Spokesmen of the Strategy Group

Prof. Dr U. Wagner *	Research Institute for Energy Economy / TU Munich
Prof. Dr J. Garche *	Centre of Solar Energy and Hydrogen Research
Dr H.J. Neef *	Research Centre Jülich

Spokesmen of the working groups

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Dr J. Wolf / Dr O. Weinmann *	Linde Vattenfall Europe	WG 2 Supply and Logistics
Dr K. Scheuerer *	BMW	WG 3 Application Technologies

Participants of the Strategy Group (* co-authors of the strategy paper)

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Dr K. Bonhoff	DaimlerChrysler
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Chr. Zeiss	German Energy Agency

Editorial

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6.2 Details on the federal state initiatives in Germany

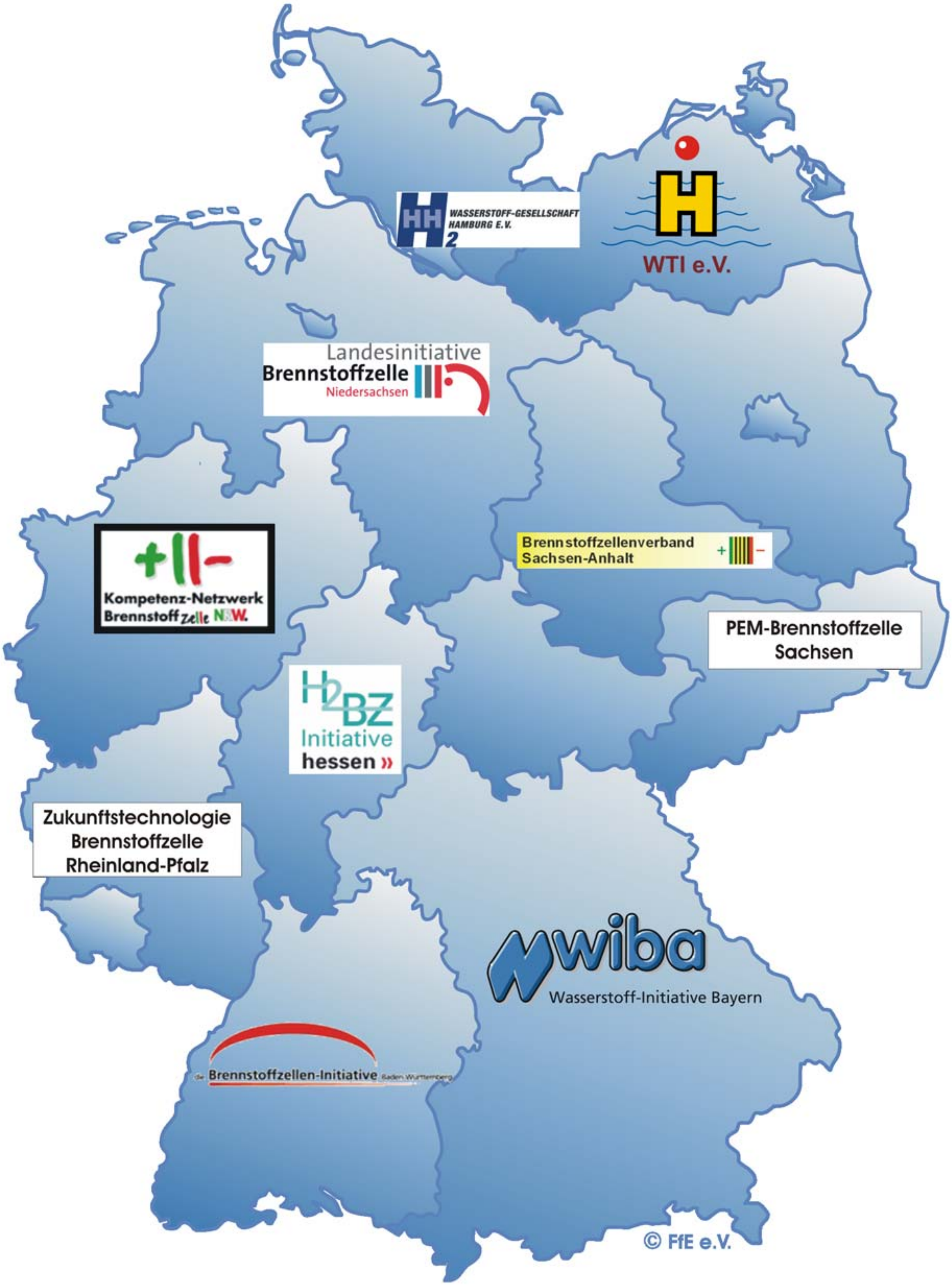

Figure 6-1: Hydrogen and fuel cell initiatives in Germany

Overview of Germany's federal state hydrogen and fuel cell initiatives

Federal State:	**Baden-Württemberg**
Name:	Fuel Cell Initiative Baden-Württemberg umbrella of: • Fuel Cell Research Alliance Baden-Württemberg (FABZ) • Fuel Cell Training Centre Ulm (WBZU) • Fuel Cell Competence and Innovation Centre of the Stuttgart Region (KIBZ)
Operator:	FABZ: Ministry of Science, Research and the Arts, Baden-Württemberg, and Ministry of Economics, Baden-Württemberg WBZU: State of Baden-Württemberg and Federal Ministry of Economics and Labour KIBZ: members
Founded:	May 2001
Funding:	total volume: approx. □ 4 million per year
Projects: (number/project volume)	projects in the fields of research, development, training, technology implementation
Members:	more than 60 members from education, research, industry and associations
Location:	FABZ at ZSW-Stuttgart, WBZU: Helmholtzstraße 6, 89081 Ulm, KIBZ at DLR Stuttgart
Contact:	FABZ: Dr W. Lehnert, WBZU: Dipl.-Ing. (FH) T. Aigle, KIBZ: Dr B. Schaible
Internet:	www.brennstoffzellen-initiative.de
E-mail	werner.lehnert@zsw-bw.de, info@wbzu.de, dbs-consult@t-online.de

Federal State:	**Bavaria**
Name:	wiba – Hydrogen Initiative Bavaria
Operator:	Bavarian Ministry of Economic Affairs, Infrastructure, Transport und Technology
Founded:	1996
Funding:	approx. □ 25 million
Projects: (number/project volume)	since 1997 more than 30 projects with a financial volume of approx. □ 75 million
Members:	approx. 50 project partners
Location:	Research Institute for Energy Economy
Contact:	Prof. Dr-Ing. U. Wagner
Internet:	www.wiba.de
E-mail:	info@wiba.de

Federal State:	**Hamburg**
Name:	Wasserstoff-Gesellschaft Hamburg e.V.
Operator:	---
Founded:	1997
Funding:	---
Projects: (number/project volume)	3 / ---
Members:	---
Location:	---
Contact:	Dr W. Fürwentsches
Internet:	www.h2hamburg.de
E-mail:	---

Federal State:	**Hesse**
Name:	Hydrogen and Fuel Cell Initiative Hesse
Operator:	members (companies, institutes, individuals); Hesse Ministry of Economics, Transportation, Urban and Regional Development via Technologie Stiftung Hessen GmbH
Founded:	April 2002
Funding:	no institutional funding
Projects: (number/project volume)	projects in the fields of research, development, training, technology implementation
Members:	15
Location:	Infraserv GmbH & Co. Höchst KG
Contact:	Dr H. Lienkamp
Internet:	www.brennstoffzelle-hessen.de
E-mail:	heinrich.lienkamp@infraserv.com

Federal State:	**Lower Saxony**
Name:	Fuel Cell State Initiative Lower Saxony
Operator:	Lower Saxony Ministry of Economics, Labour and Transport Lower Saxony Ministry of Science and Culture Lower Saxony Ministry of the Environment
Founded:	April 2004
Funding:	□ 9.5 million for 2004 - 2007
Projects: (number/project volume)	---
Members:	approx. 12 partners at present
Location:	Sperlich Consulting GmbH
Contact:	Dipl.-Ing. W. Axthammer
Internet:	www.brennstoffzelle-nds.de
E-mail	info@brennstoffzelle-nds.de

Federal State:	**North Rhine-Westphalia**
Name:	Fuel Cell and Hydrogen Network NRW
Operator:	Ministry for Energy, Transport and Spatial Planning of the State of NRW Ministry for Science and Research of the State of NRW
Founded:	April 2000
Funding:	€ 50 million from funds of the NRW Energy and Science Ministries
Projects: (number/project volume)	50 projects, total volume € 100 million
Members:	approx. 250 companies and 50 research institutions
Location:	State Initiative on Future Energies NRW, Düsseldorf
Contact:	Prof. Dr-Ing. D. Stolten, Research Centre Jülich
Internet:	www.brennstoffzelle-nrw.de
E-mail:	brennstoffzelle@energieland.nrw.de

Federal State:	**Mecklenburg-Western Pomerania**
Name:	Hydrogen Technology Initiative Mecklenburg-Western Pomerania
Operator:	Mecklenburg-Western Pomerania Ministry of Economics
Founded:	February 2002
Funding:	project funding by the State of Mecklenburg-Western Pomerania to the amount of € 614,000 until 2005
Projects: (number/project volume)	since 2000 ten projects with a volume of approx. € 15 million
Members:	approx. 19
Location:	---
Contact:	Dr-Ing. Gerhard Buttkewitz
Internet:	www.wti-mv.de
E-mail:	info@wti-mv.de

Federal State:	**Rhineland-Palatinate**
Name:	Future Technology Fuel Cell Rhineland-Palatinate
Operator:	Ministry of Economics, Transport, Agriculture and Viticulture, Rhineland-Palatinate
Founded:	April 2002
Funding:	□ 360,000 (for 3 years)
Projects: (number/project volume)	---
Members:	---
Location:	---
Contact:	Prof. Dr K. Keilen
Internet:	---
E-mail:	---

Federal State:	**Saxony**
Name:	PEM Fuel Cell Saxony
Operator:	State Ministry of Economics and Labour
Founded:	2003
Funding:	---
Projects: (number/project volume)	---
Members:	12
Location:	ZTS Centre for Technology Structure Development
Contact:	Dipl.-Ing. S. Stöhr
Internet:	http://www.pem-brennstoffzelle-sachsen.de/
E-mail:	stor@zts.de

Federal State:	**Saxony-Anhalt**
Name:	Fuel Cell Association Saxony-Anhalt
Operator:	---
Founded:	---
Funding:	---
Projects: (number/project volume)	---
Members:	---
Location:	---
Contact:	Dr I. Benecke
Internet:	http://www.brennstoffzelle-sa.de
E-mail:	info@ brennstoffzelle-sa.de

Abbreviations

ADR	Accord européen relatif au transport international des marchandises dangereuses par route
APU	auxiliary power unit
ARGEMUC	Hydrogen Project Association at Munich Airport
BERTA	Fuel cells: development and testing for stationary, mobile and portable applications
BMBF	Federal Ministry of Education and Research
BMU	Federal Ministry for the Environment, Nature Conservation and Reactor Safety
BMVBW	Federal Ministry of Transport, Building and Housing
BMVEL	Federal Ministry of Consumer Protection, Food and Agriculture
BMWA	Federal Ministry of Economics and Labour
BREZEL	VDI Fuel Cell Expert Committee
CEN	Comité Européen de Normalisation
CFRP	carbon-fibre reinforced plastic
CO	carbon monoxide
CO_2	carbon dioxide
COORETEC	CO_2 reduction technologies
CUTE	Clean Urban Transport for Europe
DMFC	direct methanol fuel cell
DVGW	German Technical and Scientific Association for Gas and Water
DWV	German Hydrogen and Fuel Cell Association
EGR	exhaust gas recirculation
ERV	electric road vehicle
FC	fuel cell
FCE	Fuel Cell Europe
GH_2	gaseous hydrogen
GRPE	Groupe de Rapporteurs de Pollution et des Emissions
GTR	Global Technical Regulation
H2/FC TP	Hydrogen and Fuel Cell Technology Platform
HC	hydrocarbon
IBZ	Fuel Cell Initiative
ICE	internal combustion engine
IEC	International Electrotechnical Commission
IPHE	International Partnership for the Hydrogen Economy
ISO	International Standards Organization
KEA	cumulative energy demand
KNRA	cumulative non-renewable energy demand
KWK	combined heat and power generation
LH_2	liquid hydrogen
LNG	liquefied natural gas
MCFC	molten carbonate fuel cell
NEDC	new European driving cycle
NGSA process	natural gas assisted steam electrolyser
NO_x	nitrogen oxides (nitric oxide, NO, and nitrogen dioxide, NO2)

PEM	polymer electrolyte membrane
PEMFC	polymer electrolyte membrane fuel cell
PtJ	Project Management Jülich
RID	Règlement international concernant le transport des marchandises dangereuses par chemin de fer
RME	rape methyl ester
SOFC	solid oxide fuel cell
SWATH	small waterplane area twin hull
TES	Transport Energy Strategy
UNECE	United Nations Economic Commission for Europe
VDI	Association of German Engineers
VDMA	Association of German Machinery and Equipment Constructors
wiba	Hydrogen Initiative Bavaria
ZIP	Federal Government's investing in the future programme