TECHNICAL REPORT SERIES

Potential for Hydrogen as a Fuel for Transport in the Long Term (2020 - 2030)

- Full Background Report -

EUR 21090 EN

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Preface

This study has been carried out by Ludwig Boelkow System Technik on behalf of the Joint Research Centre, Institute for Prospective Technological Studies (JRC/IPTS). It is part of the wider activities of the JRC/IPTS in the field of techno-economic analysis of emerging technologies in transport. Its main objective is an analysis of the prospects of hydrogen and fuel cells and the boundary conditions for the wider introduction of hydrogen as a fuel for transport. Industry stakeholders, researchers and policy makers have been consulted in the process and the findings of the study were discussed in two workshops. Other European Commission services and the Institute for Energy of the JRC were actively involved in the supervision and guidance of the study.

Hydrogen is often seen as the most promising option to replace fossil fuels in the long term. In the transport sector, it can be a suitable energy carrier and under certain conditions improve the environmental performance. World-wide energy demand will double in the next 50 years, and Europe still has very limited home-grown resources. The EU currently imports 50% of its oil, and, if nothing is done, this figure will rise to 70% in 20-30 years time. Hydrogen and fuel cell technologies could contribute to improving Europe's energy security and air quality, whilst lessening climate change.

Since many years, the EU has been supporting hydrogen & fuel cell research, and there is now a growing importance of this field, as reflected by the substantial increase in financial support. In November 2003 the European Commission Initiative for Growth included a "Quick Start Programme" of projects of public and private investment in infrastructure, networks and knowledge. This programme foresees a major ten year initiative for hydrogen-related research, production and use, with an indicative total budget of €2.8 billion of public and private funding.

In addition, the European Commission launched the European Hydrogen and Fuel Cell Technology Partnership in January 2004. The Partnership has the task of drafting a blueprint to smooth the EU's transition from a fossil fuel-based to a hydrogen-based economy, and its Advisory Council includes key players of the European hydrogen sector. Developing the new hydrogen society while gaining worldwide leadership will require a coherent EU strategy, which this European Hydrogen and Fuel Cells Technology Partnership will help devise.

This study describes a best-case scenario for hydrogen and fuel cells in transport and outlines the potential technical, economic and environmental benefits in the long term. The study also identifies the main obstacles and boundary conditions for such a wide-scale introduction. The results should be considered in the context of the boundary conditions under which the analysis has been carried out. Failure to meet these conditions would result in a significant reduction of the potential. In practical terms, this means that the potential benefit of hydrogen for transport applications is high, but the necessary investment in order to be able to reap those benefits is also considerable.

Analysing the findings of the study, five main issues that are critical for the introduction of hydrogen in transport can be identified:

- The cost of fuel cell vehicles and the cost of hydrogen as a fuel are expected to continue to fall in the future as a result of the constant improvement of technologies. A crucial condition for the reduction of costs is the realization of economies of scale in both vehicle and fuel production and the achievement of the perhaps overly optimistic goals of 50-100 $/KWh. The relative cost of hydrogen compared to conventional or other fuels is the main factor from the economic point of view. The boundary conditions for which hydrogen would have an advantage correspond to the case of high oil prices combined with either low natural gas prices or low electricity prices.

- The performance of fuel cell or hydrogen-based vehicles can potentially match that of conventional technologies. Fuel cells even offer some advantages in auxiliary power units and some niche markets. But -everything else being equal- hydrogen based technologies do not still offer enough advantages to shift user choices. It is obvious that in order to be competitive, they have to provide comparable performance at comparable cost, with accessible and reliable infrastructure. Otherwise, only a strong shift in user choices towards clean technologies would justify the substitution of the proven conventional technologies.

- Distribution and storage raise important challenges. The development of a wide network of refueling stations is a major requisite, but would need a critical mass of demand before it takes off. In this context, it is indispensable that the cost of hydrogen distribution is kept low and that its introduction is massive, so that the investment costs are justified.

- Significant environmental benefits may occur, depending on the primary energy used for hydrogen production. Electrolysis-based solutions would only be beneficial for the environment as long as the electricity used for the electrolysis is produced from carbon-free fuels. Solutions based on reformation of fossil fuels would be neutral from the environmental point of view. The introduction of hydrogen in transport would therefore be feasible only in the case of low cost of renewables in electricity generation or in the case of high-performance fuel cells with low prices of natural gas or biofuels.

- The commitment of the industry could be influenced by policy. The key industrial stakeholders (car manufacturers, refineries and fuel providers, infrastructure providers, fleet managers) will invest in a new technology only if the future market prospects are clear. The role of policy makers should therefore be that of decreasing uncertainty through suitable and timely policy measures, legislation and standards. Legislation could also influence user choices, by promoting the use of hydrogen, penalising CO2 emissions, or by limiting the use of conventional technologies in certain areas.

As a general conclusion of the study, it seems that year 2020 is too early for a wide scale introduction of hydrogen or fuel cells; it is questionable whether even year 2030 is a feasible time horizon. But it is also clear that even if the goal is the shift to hydrogen after year 2030, the preparation needs to start already.

For the JRC/IPTS

Panayotis Christidis

Hector Hernández

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Abbreviations

AFC	alkaline fuel cell
APU	auxiliary power unit
CB&H	carbon black and hydrogen process
CGH_2	compressed gaseous hydrogen
CGO	cerium gadolinium oxide
CNG	compressed natural gas
CO	carbon monoxide
CO_2	carbon monoxide
CUTE	Clean Urban Transport for Europe
DMFC	direct methanol fuel cell
EQHHPP	Euro-Québec Hydro-Hydrogen Pilot Project
FAME	fatty acid methyl ester
FC	fuel cell
FCV	fuel cell vehicle
FT	Fischer-Tropsch
GHG	greenhouse gas
H_2	hydrogen
H_2S	hydrogen sulfide
HC	hydrocarbons
ICE	internal combustion engine
IGCC	integrated gasification combines cycle
ISO	International Organization for Standardization

IT-SOFC	intermediate temperature solid oxide fuel cell
JHFC	Japanese Hydrogen Fuel Cell Project
$LCGH_2$	liquid to compressed gaseous hydrogen (refueling concept)
LH_2	liquid hydrogen
MCA	maximum credible accident
MCFC	molten carbonate fuel cell
N_2O	nitrous oxide
NO_x	nitrogen oxides
NG	natural gas
PAFC	phosphoric acid fuel cell
PEMFC	proton exchange membrane fuel cell
PSA	pressure swing adsorption
RME	rape oil methyl ester
SAE	Society of Automotive Engineers
SIGT	steam injection gas turbine
SOFC	solid oxide fuel cell
SOT	solar thermal power
UAV	pilotless aerial vehicle
ULEV	ultra low emission vehicle
UNDG-GEF	United Nations Development Program – Global Environmental Facility
YSZ	yttrium-stabilized zirconia
ZEV	zero emission vehicle

1 REVIEW AND EVALUATION OF MAIN TECHNOLOGICAL OPTIONS FOR THE PRODUCTION, DISTRIBUTION, STORAGE AND USE OF HYDROGEN AS A FUEL FOR TRANSPORT APPLICATIONS

Hydrogen technologies are in different stages of commercial development. Some technologies are fully commercial in the large scale chemical commodities market, some are commercial in the niche market of merchant hydrogen. Other hydrogen technologies are in earlier stages of development from first prototypes down to basic research.

For each component of a hydrogen fuel business, at least one technology is available as a first prototype or commercially.

For hydrogen production, many technologies are available or being developed allowing for the use of all primary and secondary energies for hydrogen generation in large centralized plants or in small decentralized units.

Distribution options include road trailer and pipeline delivery of hydrogen, which is commercial reality since many decades, or the decentralized generation of hydrogen making use of infrastructures for electricity, natural gas or biomass transport. The latter is becoming more and more common in the merchant hydrogen business.

Hydrogen conditioning includes compression and liquefaction. Both technologies are applied commercially, but have considerable further development potentials.

Hydrogen storage for transport applications requires major development efforts. Advanced conventional storage technologies are compressed gaseous storage and liquid storage in vacuum super insulated tanks. Several promising advanced concepts are in the stage of basic research.

PEM fuel cells are the most promising hydrogen application technology for road transport. They require further advances in materials and components research and development. Most importantly, medium-temperature membranes need to be developed.

All technological options for hydrogen production, distribution and conditioning, storage and use are analyzed with respect to costs, infrastructure requirements, safety risks, applicability in the various transport market segments and environmental performance.

The following table summarizes the aspects dealt with in this chapter. Technologies of hydrogen production, distribution, storage and use as well as the possible sources of hydrogen are covered. These are analyzed and evaluated concerning their costs, infrastructure requirements, risks and their applicability in the various transport market segments including niche markets. Environmental aspects are also covered, especially greenhouse gas emissions over the entire fuel path.

Table 1-1: Analysis matrix of chapter 1.

Step in H_2 pathway	
Production	technological options
	possible sources of H_2
Distribution and conditioning	
Storage	
Use	Fuel cells (AFC, PEMFC, SOFC, MCFC, PAFC, DMFC)
	Internal combustion engines
	Gas turbines

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Aspects covered
Costs
Infrastructure requirements
Risks
Applicability in various transport market segments (passenger and freight transport, public transport, ship, air, railway)
Environmental performance (greenhouse gas emissions etc.)

The aspects covered are dealt with in general in chapters 1.1, 1.2 and 1.3, while the single steps in the hydrogen pathway are analyzed in detail thereafter in chapters 1.4 to 1.8.

If not specified otherwise, the results presented represent LBST analyses.

1.1 Costs, infrastructure requirements and environmental performance

Qualitatively, there is a simple relationship between cost and environmental performance: low cost and low environmental performance versus high cost and high environmental performance.

Costs of fossil energy based fuels critically depend on the price of the primary energy. Crude oil prices have been very volatile during the last three decades with the maximum annual average price at 69 US dollars per barrel in 1981 (in real terms of 1995).

Hydrogen production and supply costs depend on various factors, the most important being the industrial context. At present, hydrogen is a chemical commodity, not a transport fuel. The industrial context of hydrogen fuel does not exist and consequently all cost projections have to be based on a future industrial scenario. Assuming niche markets for hydrogen only, production and supply costs will not be significantly different from today's prices of this chemical commodity supplied by industrial gas companies to the various small industrial consumers.

In a scenario of large scale introduction of hydrogen as transport fuel, costs will be significantly lower than today for applications such as passenger cars, as the commercial and logistic structures will be entirely different. For other applications such as air or ship transport infrastructures will be similar to today's structures of captive hydrogen production and consumption. Very large amounts of hydrogen will be produced at the point of consumption. Today these are refineries or ammonia plants, in the future these may include airports and harbors.

Cost reductions in a scenario of large scale introduction of hydrogen as transport fuel will occur through economies of number and economies of scale. In decentralized hydrogen production paths, large numbers of identical components will be required (e.g. electrolysers, filling nozzles, flow meters etc.), which are technically available or which are being developed at present, but which are not series produced so far. Increasing market penetration will allow for larger installations (e.g. larger hydrogen filling stations for privately owned cars) inducing economies of scale.

Hydrogen production and supply routes to the consumer can have very different infrastructure requirements. Decentralized onsite hydrogen production at the point of consumption makes maximum use of existing energy infrastructures, especially those for electricity and natural gas (or in the case of biomass of the road infrastructure). This point is well illustrated by the slogan "hydrogen by wire" of a North American electrolyser manufacturer.

Table 1-2: Infrastructure characteristics of onsite versus centralized hydrogen production.

Onsite production	Centralized production
Making maximum use of existing infrastructures: • Electric grid for onsite electrolysis • Natural gas grid for onsite reforming • Road for onsite biomass gasification	Hydrogen transport and distribution infrastructures needed: • LH_2 road trailers and rail cars/ containers • GH_2 pipelines
Not suitable for LH_2	Suitable for LH_2 and CGH_2

Large-scale centralized hydrogen production requires hydrogen transport and distribution infrastructures existing to a very limited extent at present. Existing infrastructures for natural gas distribution may be used for hydrogen in the future with limited modifications. First studies on admixtures of hydrogen to natural gas and on the use of natural gas distribution grids for pure hydrogen have been carried out several years ago, and first RD&D projects on an industrial level are being started at present.

Hydrogen conditioning is another important element of infrastructure. Hydrogen compression is required for pipeline transport, and for compressing the hydrogen for refueling of CGH_2 cars and other consumers. This is usually accomplished at the filling station. Hydrogen liquefaction on the other hand, will according to present projections remain a large-scale process for economic and practical reasons even though it is technically feasible also at small scale.

Hydrogen infrastructure technologies are existing to a large extent already, and may rely on existing natural gas technologies otherwise.

The build-up of a basic hydrogen refueling infrastructure is an essential challenge for the short to mid-term as it has to be in place at the beginning of the commercial introduction of hydrogen fuel cell vehicles.

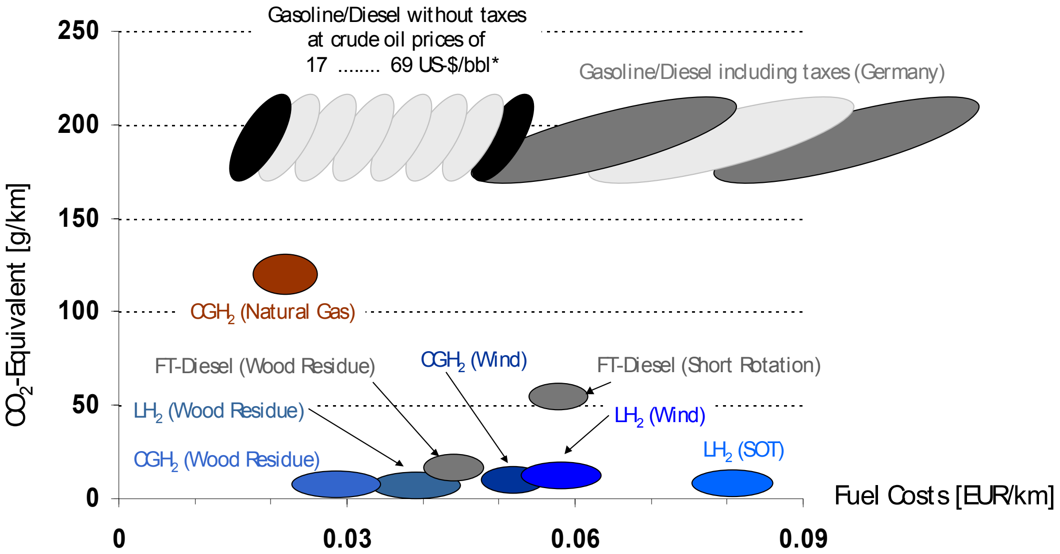
Economically, the challenge is not as big as it might appear. In the European Union including the new accession states (EU-25) some 100,000 refueling stations supply fuels to road transport. About 20% of these, or 20,000 stations, should be equipped with hydrogen dispensers before fuel cell vehicles are brought to the mass market. Assuming investment costs of 1.3 million Euro per station sums up to 26 billion Euro for a basic refueling infrastructure.

For the case of Germany as an example, this would require an initial investment of some 3.12 billion Euro for some 2,400 refueling stations. This one-off investment is slightly higher than the amount of money invested in the new installation of wind energy converters in Germany in 2001 when 2,660 MW wind power have been newly installed.

Hydrogen and conventional car fuel production and supply cost estimates are presented in Figure 1-1 per vehicle kilometer driven. Depending on the crude oil prices on the world market, hydrogen produced from natural gas and even renewable hydrogen from biomass can become cost competitive. Hydrogen from wind energy can come close to competitiveness at high historic prices of crude oil. Chapter 6 “Estimation of costs and future trends” presents more details on this subject.

Greenhouse gas emissions including carbon dioxide, methane and nitrous oxide primarily depend on the primary energy used for hydrogen production. Using renewable energies, the greenhouse gas emissions are close to zero. In comparison to conventional fossil car fuels, emissions are reduced by around 90% (Figure 1-1). Natural gas derived hydrogen used in fuel cell cars presents a certain greenhouse gas emission advantage over conventional car fuels. Chapter 5 “Life cycle analysis of the environmental impacts of the shift to hydrogen” presents more details on this subject.

Figure 1-1: Fuel supply cost projection for 2010 versus greenhouse gas emissions Well-to-Wheel.



Gasoline: ICE (Otto cycle); CGH_2, LH_2: FC; Diesel, FT-Diesel: ICE (Diesel)

* 69 US-$/bbl was the annual average crude oil price of the year 1981 in real terms of 1995

1.2 Safety risks

Safety risks associated with the production, distribution, storage and use of hydrogen largely relate to the fact that it contains large amounts of energy – a very desired feature.

This simple fact means that risks are mainly proportionate to the amount of hydrogen available in a given process or application. Decentralized hydrogen production therefore has a reduced risk as hydrogen is produced on demand and storage volumes are small.

As a gas, hydrogen displays similar safety risks as natural gas with one exception: hydrogen air mixtures may detonate (supersonic flame propagation) in certain surroundings (semi-confined or confined spaces etc.), while natural gas will explode only (subsonic flame propagation – deflagration), which causes less damage.

Reducing safety risks by detonations in semi-confined areas (tunnels, urban streets with buildings on both sides etc.) is a subject of current research. Hydrogen as a chemical feedstock has an extraordinary safety record during many decades of experiences in industrial applications. Establishing hydrogen as transport fuel extends the handling of hydrogen to laymen and large numbers of professionals. This means that new safety concepts have to be developed on the basis of existing know-how from both industrial handling of hydrogen and private handling of natural gas. Among experts there is no doubt that this can be achieved.

1.3 Applicability in various transport market segments

The applicability of the various hydrogen supply paths to the different types of transport depends to a large extent on the type of hydrogen storage onboard the vehicle. Compressed gaseous hydrogen storage is suitable for passenger cars, delivery vans, public buses, tramways and certain types of regional trains as well as for boats and small ships. Liquid hydrogen storage is suitable for these applications and additionally for airplanes and possibly large ships. It is unclear at present whether hydrogen storage is feasible for long-haul trucks with present driving distances of over 1,000 km. Hydrogen fuel is no competitive concept for long-distance/ high speed electric trains on electrified tracks.

Compressed gaseous hydrogen storage allows for decentralized onsite production concepts and for large centralized concepts alike. In the latter case, the market should be developed to a certain extent to allow for short transport distances by pipeline or in liquid form by truck.

Liquid hydrogen onboard storage requires large liquefaction plants. In the case of small consumers (cars, buses, tramways, small ships etc.) this means that one plant will supply several filling stations supporting up to hundreds of consumers each. A small number of large consumers (ships, aircraft) on the other hand may require a large plant entirely for their supply.

1.4 Hydrogen production

Hydrogen can be produced by using any primary or secondary energy carrier: natural gas, electricity (from renewable energies, from fossil energies, from nuclear power), biomass, coal, high temperature heat using thermochemical cycles (from solar concentrators or from nuclear power) etc. Hydrogen can also be produced directly from the sun and/or biomass through algae and bacteria, and it can be produced directly from the sun in photo-electrochemical reactions.

In addition, hydrogen can be a by-product of other production processes such as chlorine alkaline electrolysis for the production of chlorine.

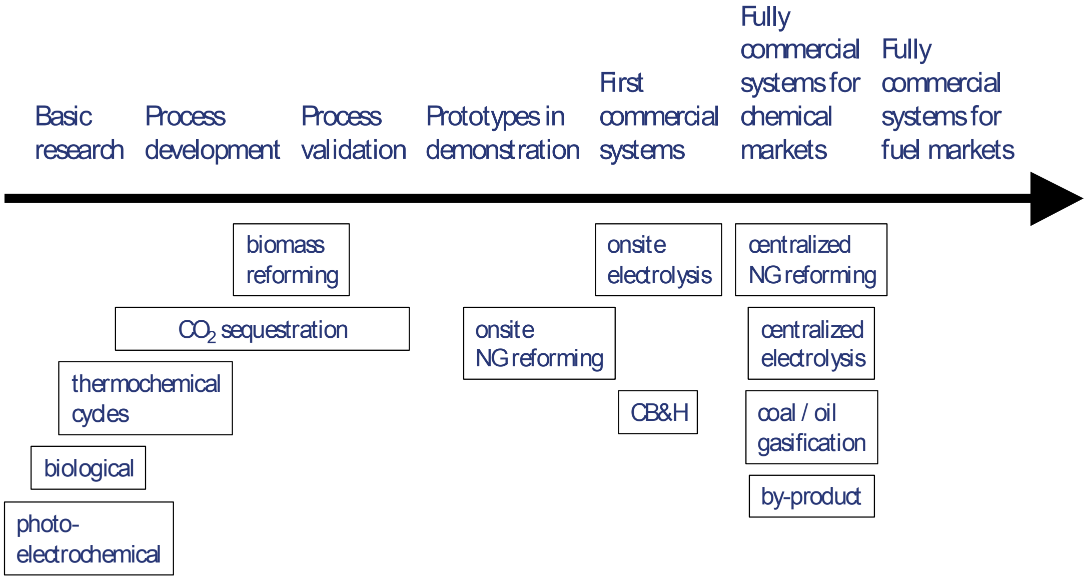
The world-wide hydrogen production at present is roughly 50 million tons per year, which in terms of energy, corresponds to about 4% of the global crude oil production of some 75 million barrels per day. This hydrogen quantity would be sufficient to supply the entire passenger vehicle fleet of Europe, Japan and the USA in case it consists of “3 liter” fuel cell vehicles (0.3 kWh/km fuel consumption).

The major hydrogen consumers today are ammonia production, refineries, methanol synthesis, chemical industry and merchant hydrogen (fat and oil hydration, float glass, electronics, metal treating etc.).

Most of the technologies discussed here are presented in more detail in [GM-WtW 2002].

Figure 1-2 gives a qualitative assessment of the present status of hydrogen production technologies.

Figure 1-2: Status of hydrogen production technologies.



1.4.1 Hydrogen from natural gas

The largest part of current hydrogen production is from natural gas in large scale steam reformers up to sizes of 100,000 Nm³/h. This technology is fully commercial and represents the most cost effective hydrogen production technology today. The hydrogen production costs are dominated by the natural gas prices. From large, centralized plants, hydrogen can be distributed to car filling stations either by pipeline in gaseous form or by truck as cryogenic liquid. Many decades of operation in industrial installations have demonstrated the excellent safety record of this technology.

Small natural gas steam reformers suitable for the onsite hydrogen production at a hydrogen filling station are in principle available. These systems are down-scaled large systems which are built as single units. Onsite steam reformers for hydrogen filling stations should be purpose-design, compact, series produced units. Some companies are developing such systems with first units available. These are either pure steam reformers or autothermal reformers, which are more compact, but have a slightly reduced efficiency. Supplying liquid hydrogen by onsite steam reforming and liquefaction is in principle technically feasible, but suffers from poor economics and a very large footprint.

The supply costs of compressed gaseous hydrogen to the car (well-to-tank) depend on the production and distribution concept. In a well established market, large-scale natural gas reforming with pipeline transport to the filling stations is the most cost effective supply path (14 –

18 €/GJ). It is assumed that a plant supplying around 400,000 fuel cell cars will deliver hydrogen to filling stations within a radius of 50 km of the plant. For larger distances, the costs will rise considerably. Onsite hydrogen production is slightly more expensive (19 – 22 €/GJ), and delivery of LH_2 from a central hydrogen plant costs 24 – 26 €/GJ. Steam reforming of natural gas represents the most cost effective hydrogen supply path for passenger cars at present natural gas prices in an established hydrogen fuel market.

The potential of this technology is limited by the availability of natural gas. Problems of supply to the European Union are anticipated for the next decade. Current natural gas consumption in the EU is very close to the current consumption of road transport fuels. It is generally agreed that a replacement of more than 10% of road transport fuels by natural gas will only be possible if natural gas will be imported from remote locations as LNG or as methanol. As the global availability of mineral oil will be drastically reduced in the 2020 to 2030 time frame compared to today other primary energy sources such as natural gas and renewable energies have to replace these quantities and/ or energy consumption has to decrease. It is more than doubtful whether natural gas will be able to replace declining crude oil production.

Hydrogen production from natural gas will be suitable for all types of transport as technologies exist for large scale centralized production and because small decentralized technologies are being developed. Large and medium scale production plants will be suitable for large fleets of road vehicles, for air and ship transport as well as for trains. Decentralized plants will be suitable for regular filling stations for passenger cars as well as for fleets of road vehicles, and for trains. For applications with a very small hydrogen throughput hydrogen production from natural gas is not suitable.

Natural gas reforming installations are limited to locations where natural gas is available. This includes natural gas pipelines with sufficient throughput, and locations where LNG could be made available in sufficient quantity.

Well-to-Tank emissions of greenhouse gases (GHG) range from 90 g/MJ (CGH_2 from EU NG mix in central plant including pipeline delivery to filling station for onboard storage pressure of 70 MPa) to about 150 g/MJ (LH_2 from Russian NG in central plant including truck delivery to filling station).

1.4.2 Hydrogen from electricity

Hydrogen production from electricity by water electrolysis has many decades of industrial application. During the last two decades, large scale water electrolysis has been replaced by natural gas steam reforming even in many areas where very cheap electricity is available (e.g. Norway). Many decades of operation in industrial installations up to 156 MW_e have demonstrated the excellent safety record of this technology.

During the last 10 to 15 years electrolysis has made significant technical progress especially with respect to efficiency and the capability to be operated with fluctuating power input. Also a trend to higher pressures can be observed. Typically new pressurized electrolysers are operated at between 1 and 3 MPa in order to save the first compression stage for hydrogen compression. Advanced technologies, although not yet having proven such long operating experiences without replacement of certain components as large-scale technology, have been simplified and improved continuously in order to enable long operating periods at low maintenance efforts. First units for distributed onsite hydrogen generation as replacement of merchant hydrogen trailer delivery are proving steadily increasing reliability since more than half a decade (in particular Stuart Energy Systems & Vandenborre Technologies, Norsk Hydro Electrolysers). These units typically are in the 30-60 Nm^3/h capacity range (i.e. 130 – 270 kW_e power range). Gradually also advanced electrolyser MW-units are under development (e.g. by GHW for unit sizes of between 1 and 3.5 MW_e). Based on these product developments several manufacturers (Norsk Hydro/ GHW, Vandenborre Technologies and Stuart Energy Systems) are conceiving electrolysis based hydrogen refueling stations for the supply of compressed gaseous hydrogen to road vehicles and other mobile applications within the coming years.

The costs of hydrogen production from electricity are dominated by the electricity costs. In the case of hydrogen production from off-shore wind power with assumed electricity costs of 6.85 Euro-cents per kWh 83% of the pure hydrogen generation costs (no compression, delivery etc. assumed) are induced by the electricity costs, 17% are induced by the electrolysis equipment.

Electrolysis has proven to be suitable for both large scale and small scale hydrogen production. Therefore, electrolysis is technically suitable for all types of transport on all scales going down to very small consumers.

Well-to-Tank emissions of GHG are spread over a wide range from 0 g/MJ (CGH_2 from wind power in onsite electrolysis unit for 70 MPa onboard storage pressure) to max. 242 g/MJ (LH_2: from EU mix electrolysis in central electrolysis plant including truck delivery to filling station).

1.4.3 Hydrogen from biomass

Hydrogen from biomass can typically be obtained in two ways: either gasification of biomass (all types of lignocellulosic material e.g. wood from residues of from dedicated plantation) or steam reforming of biogas. Biogas is obtained via anaerobic digestion of organic waste fractions or biomass from dedicated plantation, e.g. of grass.

Biomass gasification has been developed for several years. Most of the technologies produce low calorific gas containing large shares of nitrogen which is not suitable for the production of hydrogen.

For medium-scale plants (2.5-20 MW_{th}) able to produce synthesis gas for the production of pure hydrogen (or FT-diesel, methanol etc.) some development work on suitable processes is underway. So far, no prototype has demonstrated satisfactory production over longer periods. Increased development efforts are required.

In case of biomass gasification hydrogen gas is extracted from biomass via allothermal (indirect heat input) or autothermal gasification (direct external heat and oxygen input), then purified in a dust removal step, enriched in a CO-shift stage and finally subjected to pressure swing absorption for fine-cleaning.

In case of biogas reforming the methane content of the biogas is converted to hydrogen in a steam reforming step comparable to natural gas reforming.

The cultivation of any biomass has significant influence on the generation of Well-to-Tank greenhouse gas emissions. Emissions of nitrous oxide (N_2O), a strong greenhouse gas, depend on the level of fertilizer input to the plantation, the climate and several other factors. Well-to-Tank emissions of GHG are between 7 g/MJ (CGH_2 via onsite gasification of residual woody biomass for 70 MPa onboard storage pressure) to 25 g/MJ (CGH_2 via onsite gasification of woody biomass from plantation of poplar for 70 MPa onboard storage pressure).

Hydrogen from biomass can be produced in small and medium scale plants and represents one of the most cost effective hydrogen production processes directly following chemical by-product hydrogen and natural gas derived hydrogen, with the benefit of being renewable.

Biomass gasification has two limitations to process scale: On the one hand, the installation should not be too small as chemical processes suffer from reduced efficiency at small scales. On the other hand, biomass in general is not available in large quantities on a single spot, but has to be transported to the plant from decentralized sources. Transport distances must not be too large in order to allow for an energetically sensible concept. Therefore, the process scale will be suitable for filling stations for passenger cars, for fleets of road vehicles, for medium size ships or fleets of smaller ships, for small airports, and for trains.

1.4.4 Hydrogen from coal or from petroleum

During the last decade, Integrated Gasification Combined Cycle (IGCC) power plants using coal or heavy oil fractions have been commercialized. Coal and heavy fuel oil gasification can also be used to produce hydrogen.

Petroleum or coal can be gasified at between 1300 and 1400°C and at pressures between 1-10 MPa to synthesis gas, which after cooling down and separation of soot and solid particles is fed into a CO shift reactor and an H_2S/CO_2 removal stage. Then either a methanation stage or pressure swing absorption follow in order to clean up the hydrogen for use in internal combustion engines (ICEs) or fuel cells (FCs).

At present, these processes cannot be downscaled efficiently for distributed onsite use.

More than 60% of the energy content of the coal can be recovered as energy content in the hydrogen product stream of such large scale processes with capacities of larger than 100,000 Nm^3/h. Including auxiliary energy consumption in the process, efficiencies are slightly above 50%.

Hydrogen production from coal or petroleum, especially the heavy fractions in a refinery, are suitable only for very large scale consumers like airports or harbors. It will also be suitable for delivery of hydrogen to passenger car filling stations in a situation where hydrogen has reached a large market share. Also, IGCC power plants may export fractions of its syngas production for hydrogen generation and delivery, thus making the concept suitable for smaller consumers.

Well-to-Tank emissions of GHG are 252 g/MJ for hydrogen from coal delivered at 70 MPa to the vehicle tank at the filling station.

It is unclear at present in how far world-wide coal production can be extended to replace declining oil production. World-wide coal production is at about 2/3 the level of crude oil production.

Present and future discussions of the reduction of the sulfur level in transport fuels, especially in ship fuels, may lead to the availability of large quantities of hydrogen from refineries as highly sulfur-containing heavy fuel oil (HSFO) may not be sold as ship fuel any more as is the case already in the USA. These heavy fuel oils can be transformed into hydrogen, or they can be used in stationary processes such as electricity production whereas the desulfurization of heavy fuel oils is technically and economically difficult.

1.4.5 Hydrogen from fossil energy with CO_2 sequestration

1.4.5.1 CB&H Process

The development of the Kværner Process (or CB&H process) started in 1990 in Norway as a consequence of regulations calling for CO_2 taxes on flared by-product gas from off-shore crude oil production.

By pyrolysis of hydrocarbon feedstocks (e.g. natural gas, heavy fuel oil, biomass) two valuable products are obtained, hydrogen and carbon black.

The pyrolysis process uses a plasma torch implemented in a high temperature reactor. The plasma torch supplies the necessary energy via radiation and convection from the produced plasma gas to pyrolyze the hydrocarbon feedstock.

The obtained hydrogen purity from the CB&H (carbon black & hydrogen) process without additional purification steps is 98% when operated on natural gas. The thermal efficiency of the plasma generator is 97%-98%. The specific electricity consumption of the hydrogen production process is 1.1 kWh/Nm³H_2. The conversion rate of the hydrocarbon feedstock is almost 100%.

Compared to other fossil based hydrogen production processes (steam methane reforming, partial oxidation etc.) the CB&H process has several advantages: Lower hydrogen production costs than CO_2 free production processes (if renewable electricity is used for the CB&H process), higher feedstock utilization rate, high feedstock flexibility, high modularity of the process.

The first commercial plant located in Montreal, Québec, Canada, consists of two modules in the project's first phase and has an annual capacity of 20,000 t of carbon black and of 50 million Nm³ of hydrogen. The installed electric capacity of the plasma generator is 6 MW_e. The investment costs are in the order of 65 million $-CDN. The plant is operative since mid-1999. Since then, no further developments have taken place and the commercial status of the technology is unclear.

The modular concept has been engineered and costed by Kværner for capacities ranging from 1 to 360 million Nm³/yr. Larger capacities can easily be configured by adding modules.

Gross hydrogen generation costs (excluding benefits from carbon black and steam sales) of 0.1247 US$/Nm³$H_2$ (11.5 US$/GJ) or net costs of 0.0661 US$/Nm³$H_2$ (6.1 US$/GJ) can be achieved for a large-scale CB&H plant with a capacity of 280,000 Nm³H_2/h. According to Kværner this would be competitive with a comparable natural gas steam reforming plant which would yield hydrogen costs of 0.06711 US$/Nm³$H_2$ plus 0.01793 US$/Nm³$H_2$ for CO_2 sequestration, thus totaling 0.0851 US$/Nm³$H_2$ (7.9 US$/GJ).

The very small processes (1 to 10 million Nm³/a) are suitable for onsite hydrogen production for filling stations for passenger cars, for fleets of road vehicles, for medium size ships or fleets of smaller ships, for small airports, and for trains. The large processes are comparable in size with large-scale industrial NG steam reformers. These are suitable for centralized production with hydrogen delivery to the smaller consumers mentioned above, and for large consumers such as airports and harbors.

Well-to-Tank greenhouse gases depend heavily on the source of electricity used. For the European electricity mix, the emissions are 49 g/MJ for the supply of CGH_2 to 70 MPa car tanks. For renewable electricity, the emissions go down to practically zero.

1.4.5.2 CO_2 sequestration

CO_2 sequestration is mainly discussed in connection with electric power production with some discussion on hydrogen production.

CO_2 sequestration can be performed by chemical solvent scrubbing, physical solvent scrubbing, adsorption, membranes, cryogenics, chemical looping combustion and ceramic membrane separation. The most promising approach is pre-combustion capture e.g. in natural gas steam reforming including CO-shift which generates a very hydrogen-rich synthesis gas and a quite concentrated CO_2 stream. Due to the high pressure and the high partial pressures CO_2 can easily be extracted. Besides established chemical processes advanced concepts with reactive membranes are under development. Efficient separation works only in large-scale centralized units providing hydrogen in large amounts. Today's industrial steam reforming plants typically range from 50,000 to 100,000 Nm^3H_2/h (150-300 MW thermal hydrogen equivalent, or about 200 – 400 MW thermal natural gas equivalent). CO_2 sequestration rates of up to 85% and 97% can be achieved for natural gas and coal, respectively. Additional primary energy requirements for CO_2 separation and storage are around 4% for hydrogen production from natural gas, and around 17% for hydrogen from coal. These values are valid for short CO_2 transport distances around 70 km.

Natural gas reformed hydrogen delivered to the filling station for 70 MPa vehicle tanks is expected to cost about 14 – 18 €/GJ, hydrogen from coal costs 19 – 21 €/GJ. Studies suggest that CO_2 sequestered hydrogen from natural gas or coal will cost about 25% or 28%, respectively, more than the equivalent process without sequestration; other studies indicate higher additional costs. This results in hydrogen costs at the filling station of 16 – 20 €/GJ for natural gas including sequestration, and of 22 – 24 €/GJ for coal including sequestration, which is similar to CGH_2 supply costs from biomass [CSIC 2002], [Enquête 2002], [DTI 2002].

Well-to-Tank GHG emissions for coal are 49 g/MJ (for comparison: 252 g/MJ without sequestration), for natural gas the emissions are 29 g/MJ (for comparison: 94 g/MJ without sequestration).

The disadvantage of CO_2 sequestered natural gas derived hydrogen is that it is limited to large-scale centralized production and cannot be realized in smaller decentralized plants or even as onsite compact reformer technology. Thus, it is not attractive for early hydrogen refueling infrastructure build-up scenarios for vehicles between 2010 and 2020.

Nonetheless, it might be applicable to larger scale supply schemes for ships and aircraft about the time they become commercial, possibly between 2015 and 2020.

CO_2 sequestration is limited by the availability of storage capacities. For Europe, large CO_2 storage capacities compared to CO_2 emissions are located in Norway, the United Kingdom, the Netherlands and Denmark. The other countries for which data are available have only insignificant storage capacities. Ocean storage of CO_2 is being regarded as waste disposal and thus violates the UN OSPAR and the London Conventions. Large additional storage capacities are potentially available in unconfined aquifers, for which the long-term stability (confinement of CO_2) is not proven.

The assessment of technological and economic development risks and obstacles varies considerably in the different literature sources. Based on expert hearings and contracted studies, a German parliamentary commission in July 2002 comes to the following unanimous conclusion: “CO_2 separation and storage are a potential option for the mid to long-term perspective under reserve of significant technical innovation, of confirmation and extension of knowledge about the various storage options, of ecological compatibility and of social acceptance.” [Enquête 2002].

Safety risks of CO_2 capture and storage are related to the fact the CO_2 is heavier than air. In case of leakages CO_2 can accumulate in depressions killing human beings and animals by asphyxiation.

1.4.6 Other hydrogen production technologies

1.4.6.1 High temperature heat using thermochemical cycles (nuclear, direct solar)

Direct thermal steam dissociation occurs at temperatures above 2,000 K. These temperature levels are so high that the resulting materials problems indicate that such processes will not be feasible economically. Thermochemical cycles in contrast to direct thermal water dissociation utilize the coupling of two or more balance reactions which allow separate process steps at different temperature levels and thus the separated release of hydrogen and oxygen at temperature levels of below 1,200 K. Several process steps mean a complication of the entire process technology which for many thermochemical processes often endangers economic feasibility. Hybridized cyclic processes in which one of the process steps is realized as an electrolysis step overcome this difficulty and can be realized with attractive total thermal yields as two step processes/ cycles. High temperature dissociation of sulfur trioxide (H_2SO_4) to sulfur dioxide and oxygen together with an electrolytic process step, consisting of anodic reaction of sulfur dioxide and cathodic hydrogen release, may serve as an example:

$$H_2SO_4 \xrightarrow{\text{1,000 K}} H_2O + SO_2 + \tfrac{1}{2}\,O_2$$

$$SO_2 + 2\,H_2O \xrightarrow{\text{Electrolysis}} H_2SO_4 + H_2$$

There are no publicly available data on cost assessments of this hydrogen production method. Costs will depend significantly on the supply costs of high temperature heat. In the case of nuclear energy the “true” costs are subject to controversial debate. The same holds true for the risks associated to the use of nuclear fission for energy supply. Risk is defined as the probability of an accident times the damage cause by it. Even if the risk is at acceptable levels, the potential damage of a maximum credible accident (MCA) is not acceptable to many people and countries. In addition, the question of the ultimate nuclear waste disposal is still unsolved after several decades of commercial nuclear power production. Within EU-15, only four countries continue to use and develop nuclear power while four have no plans to extend use of nuclear energy or have made concrete decisions to end its use, and the remaining countries have either already ended nuclear power production or have never used it.

Other risks depend on the chemicals used in different candidate cycles and cannot be evaluated in general.

The applicability of such processes depends on various factors. One factor is the location of the heat source. For direct solar heat as well as for nuclear reactors locations are limited by certain factors. In the former case, the level of direct insulation should be high limiting the installations for the European case to locations in southern Spain, southern Italy, southern Greece and North Africa. In the latter case, locations are limited by the acceptance of nuclear energy by the population and by further factors. In general, nuclear installations are located as far away as possible from urban centers, which are the large consumers of transport fuel.

This means that this technology is intimately connected to long transport distances of hydrogen fuel, which may have a negative effect on commercial viability.

1.4.6.2 Biological hydrogen production

In natural photosynthesis occurring in green plants and green and blue algae the oxygen released results form the splitting of water. Technical utilization of photosynthetic mechanisms aims at recovering the hydrogen which is released within this dissociation process. In the anoxygenic photosynthesis an organic substrate (glucose = $C_6H_{12}O_6$) reacts with water and light radiation according to:

$$\text{Glucose} + 6\ H_2O + 24\ h\nu \quad \rightarrow \quad 6\ CO_2 + 12\ H_2$$

If this process is combined with the synthesis of glucose from organic matter (e.g. organic waste) by algae, both oxygen and hydrogen are produced. Due to the spatial separation of the algae from the hydrogen producing bacteria in this compound system hydrogen and oxygen can be collected separately in an easy way .

Fermentation processes follow the two reaction equations:

$$\text{Glucose} + 2\ H_2O \quad \rightarrow \quad \text{Acetate} + 2\ H^+ (=2\ CH_3COOH) + 2\ CO_2 + 4\ H_2$$

$$\text{Glucose} + 6\ H_2O \quad \rightarrow \quad 6\ CO_2 + 12\ H_2$$

Yields lie typically in the order of 0.5 m^3 H_2/ kg carbohydrate. Research is under way in order to come to sustainable biohydrogen production process optimization ensuring stable long-term generation of hydrogen on high strength complex biomass substrates at increased hydrogen yields (e.g. sparging with anaerobic digester biogas, operation at thermophilic temperature).

Biological hydrogen production is still in the phase of basic research not allowing for economic assessments.

1.4.6.3 Photo-electrochemical hydrogen production

Photo-electrochemical hydrogen production is similar to photovoltaic power generation in that solar radiation is directly converted into the desired secondary energy carrier by semiconductor materials. The drawback in directly producing hydrogen is that oxygen is produced at the same time with both gases mixed at the outlet of the installation. This increases the complexity of the installation as the gases have to be separated, and it is an important safety risk as the gas mixture is explosive.

Photo-electrochemical hydrogen production is still in the stage of basic research not allowing for economic assessments.

More than 40 years of publicly funded research and development on hydrogen photosyntesis from water have not yet resulted in any photocalytic material with acceptable production costs or lifetime or efficiencies. Especially the costs for the separation of the simultaneously produced H_2 and O_2 are prohibitive. On the other side, the failure to achieve any set goals cannot be traced back to lack of effort or intelligence, rather, it can be linked to the approach of identifying new material systems. Conventional chemical methods of making and testing materials one at a time are too slow and not sufficiently systematic.

1.4.6.4 By-product hydrogen

In chlorine-alkaline electrolysis which serves for chlorine gas production, hydrogen is generated as a by-product. Since the late 19th century Chlorine (Cl_2) production has increased significantly on world-scale and has reached a level of approx. 35 million tons per year. More than 10% are produced in Germany. 95% of all chlorine is produced in electrolysis processes. The electrolytic Cl_2 generation is based on the input of electrical current into a diluted solution of metal chloride, e.g. NaCl brine.

In principle three electrolysis technologies exist: the amalgam process, the diaphragm process and the membrane process. The latter two are two chamber cell systems in which the diaphragm or the membrane separate the gas exchange from one chamber to the other. Most recent plants are designed according to the membrane electrolysis process. The amalgam process involving mercury is not used in new installations anymore.

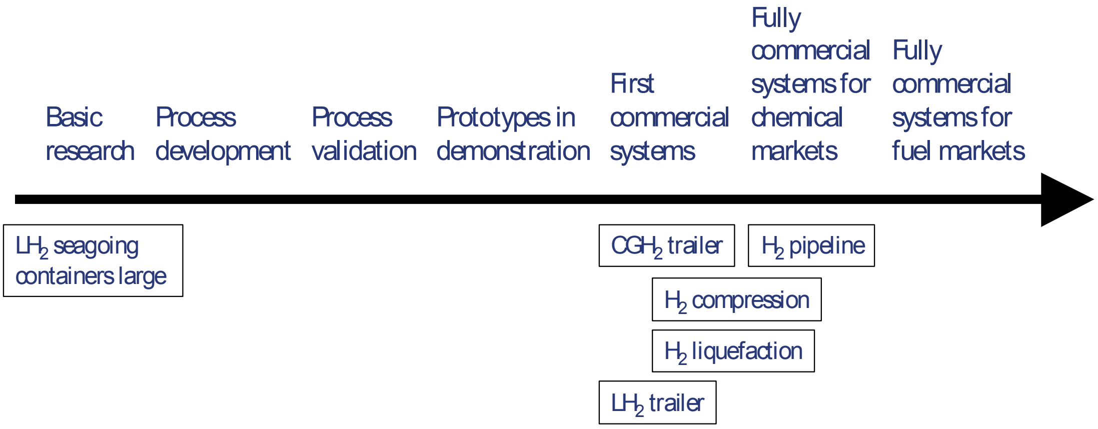
By definition, by-product hydrogen is limited in quantity and does not have well-defined production costs. Supply prices of by-product hydrogen will depend on the market situation. An indicator may be the price of natural gas as today by-product hydrogen is mostly used to substitute natural gas in thermal processes. Consequently by-product hydrogen is one of the cheapest hydrogen supply pathways at present, cheaper than steam reforming of natural gas. This favorable economic situation can be maintained if the hydrogen is used close to the chemical plant usually located in population centers.

The GHG emissions to be allocated to the direct use of by-product hydrogen are those of natural gas combustion as it will be balanced by the purchase of additional quantities of natural gas. This is equivalent to a 25% reduction in GHG emissions compared to hydrogen production by steam reforming of natural gas[1].

1.5 Hydrogen distribution and conditioning

Figure 1-3 gives a qualitative assessment of the present status of hydrogen distribution and conditioning technologies.

Figure 1-3: Status of hydrogen distribution and conditioning technologies.



1.5.1 Gaseous hydrogen

1.5.1.1 Gaseous hydrogen transport

Gaseous hydrogen can be transported in pressurized bottles (typically 20-30 MPa) in single bottles, bundles or bundle trailers, in tube trailers (typically 20 MPa) and in pipelines (final distribution at pressure levels of between 0.01 and 2 MPa and long distance transport between 1.1 and 30 MPa). Steel bottles and pipelines have more than half a century of industrial experience with excellent safety records. Composite materials bottles at 30 MPa are in service since about one decade also with excellent safety records. Also transcontinental pipelines have been investigated in several design studies for pipelines of 2,000 to 3,300 km length, pressures of up to 10 MPa and diameters of up to 1,400 mm (the most recent one by the Japanese initiated International Hydrogen Pipeline Forum for a pipeline from Russia via China to Japan).

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[1] 83 g/MJ for hydrogen from large scale natural gas steam reforming free plant versus 62 g/MJ for production, delivery and combustion of natural gas.

Trailer transport of CGH_2 can be realized only up to about 6,000 Nm^3 and at low energy efficiencies which limits its application to short distances of below 200 km and to small quantities (i.e. small volumes and frequencies). In comparison, a 40 m^3 LH_2 trailer transports about five times the hydrogen amount.

Hydrogen pipeline transport has been performed over distances of up to to 300 km for many decades. It is the appropriate transport method for large volumes at high utilization rates. More than 1,000 km of industrial hydrogen pipelines are operative worldwide, mainly in the USA and Europe (France, Germany and Belgium).

In comparison to natural gas the pipeline transport costs of hydrogen are up to 1.5 times higher. The main reason is that for hydrogen approx. a 3.5 times higher compression energy is required for transporting the same energy equivalent.

A significant improvement in operating efficiency can be achieved by utilization of high input pressures as provided by pressure electrolysers or PSA-stages after natural gas reforming (typically 2 to 3 MPa). This can reduce the initial hydrogen compression efforts at the beginning of the pipeline by a factor of up to 5.

1.5.1.2 Hydrogen compression

Hydrogen compression is achieved by use of piston, diaphragm and hydraulic compressors. Typical suction pressures lie between 0.1 and > 3 MPa and discharge pressures can be above 120 MPa depending on the type and application (e.g. large scale industrial or small scale onsite service station compression). Electric power requirements for five stage compression from a suction pressure of 0.2 MPa to discharge pressures of 45 and 88 MPa lie between 0.11 and 0.13 kWh_e/ kWh_{CGH2}, respectively. At a suction pressure of almost 3 MPa these values drop significantly to between 0.05 and 0.07 kWh_e/ kWh_{CGH2}, respectively.

1.5.2 Liquid hydrogen

1.5.2.1 Hydrogen liquefaction

Hydrogen liquefaction is an industrial technology since the 1960s when in the US large liquefiers were built for the US space program. Large in this context means liquefaction capacities in the order of between 20 and 55 t/d. The total capacity of liquefiers built worldwide since 1957 reaches some 270 t/d. Not all of these plants are operative anymore. European liquefaction capacity in three plants is 19.4 t/d, which could roughly support 58,000 fuel cell cars.

The major operating cost factors of a state-of-the-art large liquefier are service capital (50-55%), electric energy requirements (~ 30%) and maintenance (~ 8%). The only factor which can be influenced for a given plant size/ type is electricity cost.

1.5.2.2 Liquid hydrogen transport

Today, LH_2 is transported in cryo-containers or trailers of typically up to 41 m^3 or 53 m^3 at cryogenic temperatures of about 20K (- 253°C). Larger containers of between 300 and 600 m^3 are only in use for space projects like Ariane and Space Shuttle. Detailed design studies for large seagoing containers for capacities of 3,600, 24,000, 50,000 and 100,000 m^3 have been performed in Europe (EQHHPP, GL/HDW/LGA) and Japan (IHI in WE-NET). The autonomy of these transport vessels (i.e. the time before the first evaporated LH_2 has to be blown off in gaseous form) depending on layout criteria for design is between 30 and 60 days.

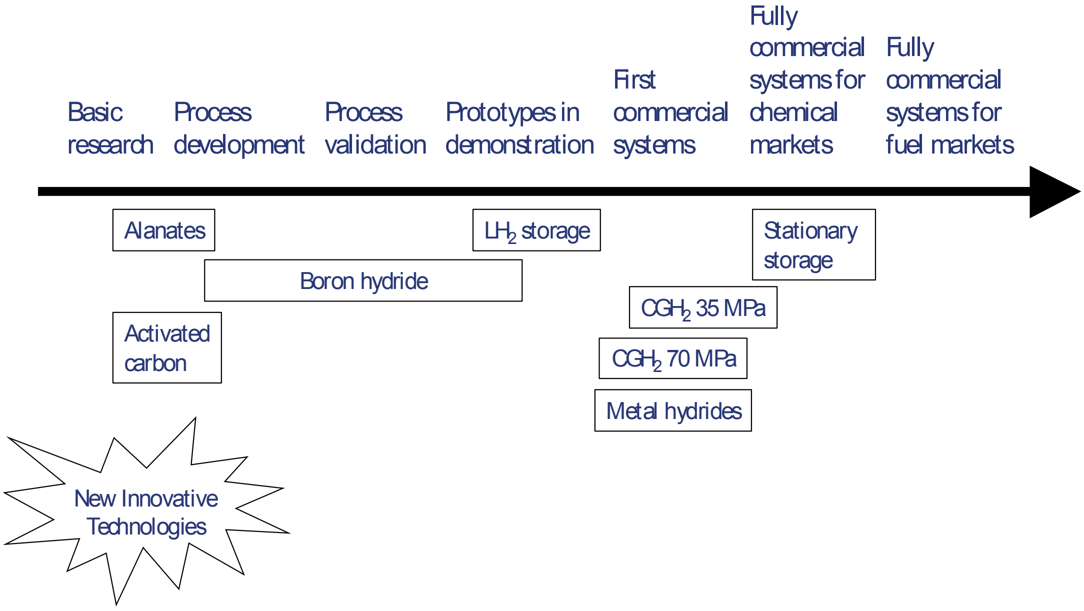
LH_2 would be delivered to a refueling station by trailer transport comparable to today's delivery of liquid hydrocarbon vehicle fuels.

LH_2 trailers are sold in single units. The overall number of large LH_2 trailers in Europe is certainly less than 20. Establishing hydrogen fuel with the need for larger numbers of LH_2 trucks economies of number will certainly allow for cost reductions of 30% to 50%.

1.6 Hydrogen storage

Figure 1-4 gives a qualitative assessment of the present status of hydrogen storage technologies.

Figure 1-4: Status of hydrogen storage technologies.



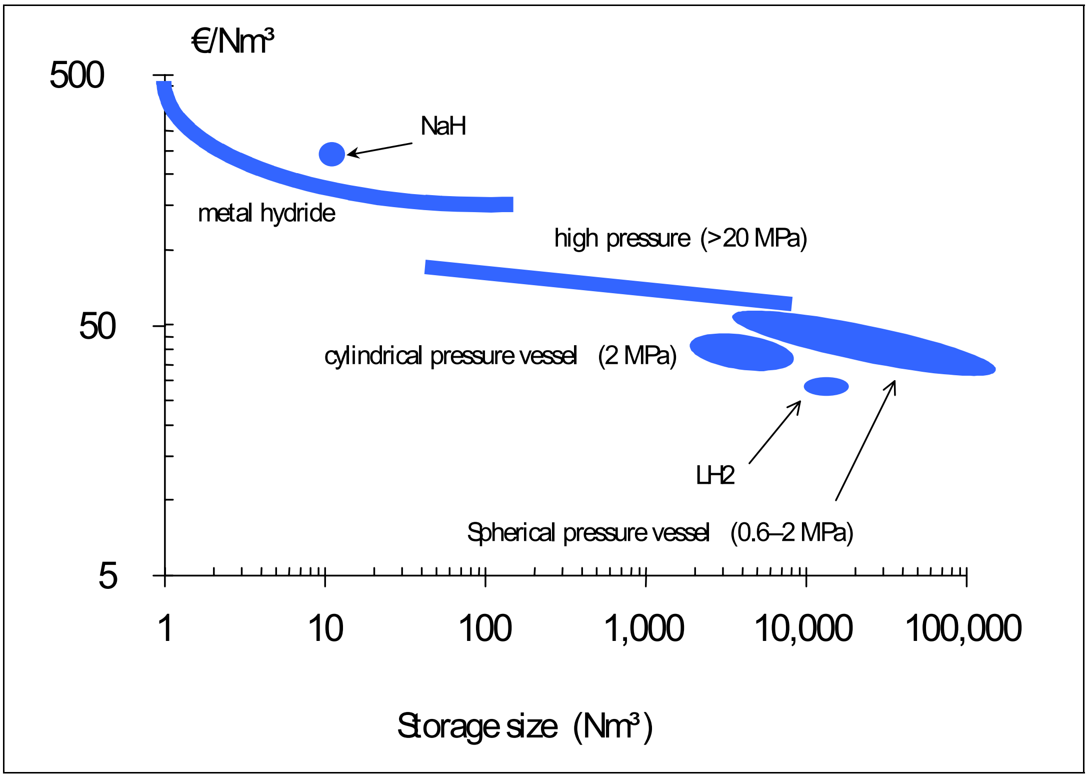
1.6.1 Stationary hydrogen storage

Hydrogen can be stored in small and large quantities using a variety of different storage methods, such as gaseous or liquid hydrogen storage, or physically or chemically bound to the storage material. Small amounts of gaseous hydrogen can be stored in bottles or tubes, larger amounts in gasometers and very large amounts in underground aquifers, salt caverns or depleted oil or gas deposits.

Liquid storage is feasible in small volumes in so-called cryostats, in medium size volumes in cylindrical storages of some tens or hundreds of cubic meters or in larger spherical or cylindrical storages with several thousands of cubic meters. Physical storage is possible in metal hydrides. Chemical storage in so-called chemical hydrides (e.g. methyl-cyclohexane/ toluene, sodium-borohydride) are proven concepts for stationary storage of hydrogen even though they are not applied commercially thus far.

The investment costs of stationary hydrogen storage depend on the size of the tank, as shown in Figure 1-5.

Figure 1-5: Investment costs of hydrogen storage depending on the storage size.



1.6.2 Onboard hydrogen storage

Technologies for hydrogen storage onboard road vehicles are compressed and liquid hydrogen as well as classical and novel metal hydrides and adsorption in carbon structures.

1.6.2.1 Applicability in various transport market segments

State-of-the-art technologies for hydrogen storage onboard road vehicles are compressed and liquid hydrogen storage. Exotic methods are classical (low temperature titanium or vanadium containing) and novel (high temperature aluminum or magnesium containing) metal hydrides, and in the future also adsorption in carbon structures. These methods may also be applicable to tramways and regional trains as well as boats and small ships.

A pressure of 35 MPa in CGH_2 storage tanks is regarded sufficient for most city bus and urban utility vehicle applications whereas 70 MPa are a must for passenger cars (due to their requirements in operating range and consumer space).

High temperature hydrides show the best gravimetric storage densities of up to 8% by weight[2], but due to their high release temperatures of above 200°C they are not suitable for vehicle applications. With low temperature hydrides only low gravimetric densities can be achieved which are not sufficient for automotive applications either. Medium temperature hydrides with release temperatures of around 100°C up to 200°C seem to be the type of hydrides closest to fulfilling important automotive requirements. Metal hydrides show very high volumetric storage densities.

For large consumers such as railways, ships and aircraft only liquid hydrogen storage seems to be realistic. Otherwise the necessary storage volumes would create serious problems with regard to size and cost. For large aircraft, LH_2 storage reduces overall weight by up to 30% compared to kerosene jets representing an important cost advantage.

1.6.2.2 Infrastructure requirements

Compressed hydrogen storage requires refueling stations being able to supply hydrogen at pressures above 70 MPa (for high pressure vessels) or above 35 MPa (for 35 MPa onboard storage). This in turn requires adequate compressors and storage devices at the station while their proper size depends on the demand patterns. The hydrogen might be produced either onsite at the station, or transported from central plants in pipelines or in trucks in liquid form. If produced onsite, access to water and electricity or to natural gas or to biomass is necessary to feed a local electrolyser, a natural gas reformer or a biomass gasifier, respectively. Onsite hydrogen production requires at least space for dispenser, storage and hydrogen generator, and safety distances comparable to compressed natural gas refueling stations (see chapter 1.7 on filling stations).

Liquid hydrogen usually is supplied to the station by trucks.

Metal hydride storage devices need low pressure filling (usually below 5 MPa) and cooling extracting the adsorption heat during refueling.

Novel materials such as carbon storage devices would require cryogenic temperatures (below 190 K) and low pressure (below 5 MPa) refueling at the station.

1.6.2.3 Costs

Costs are highest when exotic materials or complicated storage structures are involved. This is the case for liquid hydrogen storage where complicated production processes with many insulating layers within an evacuated tube are involved. Mass manufacturability (suitable designs, manufacturing technologies) is a key to achieving acceptable costs of LH_2 storage sys-

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[2] For all metal hydride systems storage densities have to be differentiated very carefully between the pure metal powder and the entire tank system (powder + containment + heat flow and gas in/outlet management + outer tank shell).

tems. Low temperature metal hydrides on the other hand include expensive materials such as Titanium or Vanadium, which prohibits their use in road vehicles.

High pressure storage systems are manufactured using composite materials for the storage vessel. Several manufacturers (Dynetek, Quantum, Lincoln) have developed first 70 MPa storage systems and received approval for vehicle use. Others (Composite Acquitaine, Luxfer, SCI and Ullit) are on the way to develop and approve such tank systems. Practically all 70 MPa tank systems have pressure reduction valves integrated into the tank systems in order to avoid high pressure releases of hydrogen in case of accidents. At present it is not yet clear which liner system for the inner tank will suit all requirements best, the metallic (low permeability, good connection to tank boss) or the plastic (lower weight, no stress-crack corrosion) liner.

Presently costs of composite materials tanks are extremely high. Due to mass manufacturing it is hoped to reduce them to acceptable levels for automotive applications. Commercial application will take place when first mass manufactured vehicles enter into the market, which is expected around 2010. Then mass manufacturing of these tanks will have started with significant economies of number. Cost goals are 200 – 500 € for a single storage tank compared to 25,000 € today. Prerequisite for such cost reductions are large numbers of units per year in the order of several hundreds of thousands per manufacturing line.

Lowest cost could be achieved with activated carbon materials at moderate cryogenic temperatures and moderate pressure once their acceptable performance for typical uses can be shown.

1.6.2.4 Risks

The risks of using hydrogen fuel in transport are different than those known for conventional fuels such as gasoline, diesel, CNG or LPG, but not necessarily higher in the various aspects.

Two types of risks are associated with hydrogen storage: The release of large quantities of hydrogen within a short timeframe, and the slow release of small quantities of hydrogen within confined spaces in which the hydrogen can accumulate. In the former case, after mixture with air and ignition, a detonation can occur depending on the geometry of the surrounding area causing considerable damage. In the latter case, hydrogen can accumulate over time in cavities and can detonate at ignition.

Hydrogen has a high diffusion rate, and it is lighter than air. In case of a spill of hydrogen it dilutes rather quickly in the air and vanishes upwards.

Compressed gaseous storage of natural gas in 20 MPa steel and composite materials storage tanks is a worldwide proven technology with more than 1 million cars on the road. Hydrogen, due to its much lower volumetric energy density requires higher pressures for achieving acceptable operating ranges. 70 MPa hydrogen storage contains almost as much energy as 20 MPa natural gas storage. Presently 35 and 70 MPa H_2 storage is in use (35 MPa) or under development (70 MPa). 35 MPa are regarded sufficient for most city bus and urban utility vehicle applications whereas 70 MPa are a must for passenger cars (due to their requirements in operating range and consumer space).

The safety risks of 20 MPa and 70 MPa compressed storage systems are similar to each other, even though potential safety risks increase slightly with higher pressures. The probability of a destruction of the pressure cylinder with associated high pressure gas release, e.g. in a road accident, is rather low. Pressure cylinders are very robust as they have to withstand pressures of 2.35 times the design pressure (e.g. 70 MPa). Pressure vessels are intrinsically gas tight as any tiny leak would very quickly result in the release of the entire gas content. It is more probable that safety valves are cut off the pressure vessels in accidents. In this case, only very small amounts of hydrogen are released as the pressure reduction valves integrated into the cylinder will shut immediately. Nonetheless, accident scenarios can be envisaged in which the full storage pressure may cause an immediate release of the fuel content with major consequences for the direct vicinity of the damaged tank.

The major drawbacks of a compressed storage device beside the high pressure is the nonconformability together with the relatively low storage density. Storage vessels always have cylindrical or elliptical design which requires suitable space on board a vehicle.

Liquid hydrogen storage vessels will not release hydrogen at high pressures within seconds in case of an accident. They will release cold, gaseous hydrogen in most accident scenarios within several minutes as the liquid hydrogen is warmed up by the ambient temperatures. For this, small damages to the outer shell of the storage vessel are sufficient as they result in an immediate loss of the insulating properties of the vacuum super insulation. Only in case of a complete destruction of the LH_2 tank, cryogenic liquid hydrogen will be spilled within seconds.

During regular operation heat intrudes into liquid hydrogen tanks during periods when no hydrogen is withdrawn from the tank. Gas pressure within the tank builds up and, after a certain time, reaches the pressure at which the pressure relieve valve opens. Measures have to be taken which avoid the accumulation of hydrogen during a possible boil-off in closed rooms such as garages. In the car, boil-off hydrogen will be burnt before release (usually a catalytic burner). In addition some venting or other measures might become necessary or at least advisable for garages, under ground parking etc.

Liquid hydrogen storage is nonconformable as well. However, the advantage of LH_2 is the high storage density which comes close to one fourth of the volume of a conventional gasoline storage system.

Metal hydride storage avoids both problems due to its low pressure and due to working temperatures close to ambient temperature.

Also hydrogen adsorption storage in activated carbon or novel materials (comparable to, but better than activated carbon) might offer an opportunity to overcome both problems. Reduced pressure and reduced insulation efforts might allow for the construction of rectangular tanks. In addition even at cryogenic temperatures of 80 K or above, the boil-off problem might be considerably reduced compared to liquid storage. Similar improvements without the need for even moderate cryogenic temperatures may be provided by alanates, a special novel form of metal hydrides. The main motivation for the development of these advanced hydrogen storage concepts is the promise to achieve storage densities similar to liquid hydrogen at reduced safety risks.

Chemical hydrides have the risk of toxicity of the involved materials (e.g. toluene is carcinogenic), and recycling issues remain unsolved.

1.6.2.5 Environmental performance

The environmental aspects of hydrogen storage are the material requirements for tank manufacturing and recycling, and the energy consumption for conditioning the hydrogen to the requirements of the storage concept.

Metal hydrides in general involve metals which consume a lot of energy during mining and refining.

Liquefaction of hydrogen is the most energy consuming conditioning method. In a Well-to-Wheel analysis this is partly compensated by low transport energy requirements for LH_2 compared to gaseous hydrogen, or compared to the lower efficiency of onsite versus large-scale hydrogen generation technologies. The compression energy requirement for 70 MPa CGH_2 storage is lower than the liquefaction energy requirement.

Boron-based chemical hydrides release 0.35 to 0.5 kWh of heat for the release of 1 kWh of hydrogen. In addition to the fact that this heat has to be removed in a car system, which is not an easy task, this means that this energy has to be spent during fuel production from hydrogen, and it is lost during use.

Chemical hydrides need to be recycled. This usually is connected with high energy requirements and accompanying greenhouse gas emissions.

Activated carbon storage would have the lowest environmental impact since the basic material is simple (carbon) and pressure requirements are moderate. The major impact would arise from low temperature processing of hydrogen and from the containment material to stabilize the storage device at moderate pressures.

1.7 Hydrogen filling stations

In a future well-established hydrogen mass market, typical filling stations having 4-8 hydrogen filling nozzles for passenger cars will sell 3 to 6 million Nm^3 of hydrogen per year (500 to 1,000

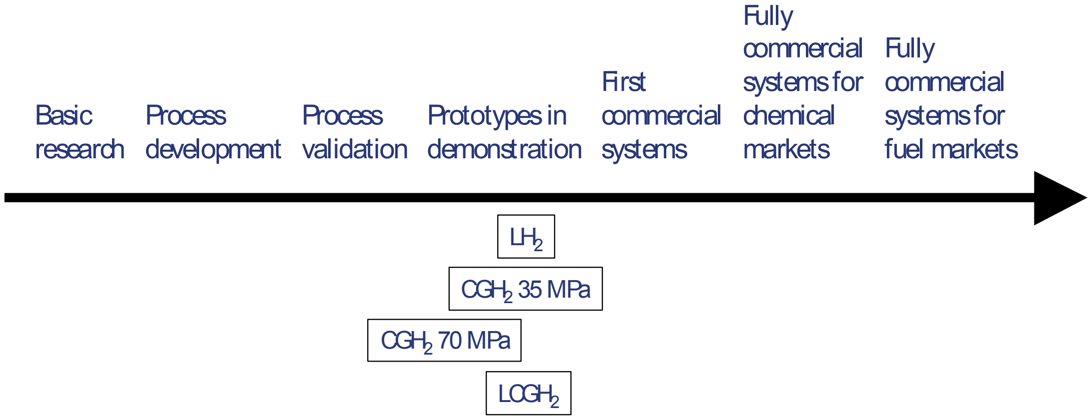
Nm³/h onsite production capacity) supporting some 2,500 to 5,000 fuel cell passenger cars (180 to 360 filling operations per day)[3].

Of the approximately 70 hydrogen refueling stations operative or in planning worldwide the majority of 57 dispenses compressed gaseous hydrogen (CGH_2) [h2cars 2003]. In 46 hydrogen is produced and dispensed as gas whereas in 11 CGH_2 is obtained from LH_2 via evaporation and compression ($LCGH_2$). 11 stations dispense LH_2 only. The reasons for this distribution is related to the fact that most prototype vehicles use CGH_2 as storage medium and fuel, and only very few vehicles (e.g. by BMW, several by GM and one by DaimlerChrysler) use LH_2. The reason for $LCGH_2$ dispensing are the relatively low investment costs for a low volume low frequency refueling station (as is the case with many stations at present).

At present Europe leads in the number of hydrogen refueling stations (27) ahead of the US (18), Japan (14) and China (2). The largest single national pool behind the US is Germany (15). In these numbers also in-company stations are counted for all regions.

Figure 1-6 gives a qualitative assessment of the present status of hydrogen filling station technologies.

Figure 1-6: Status of hydrogen filling station technologies.



The single largest filling station projects are the CUTE project in Europe with 9 stations, the JHFC program in Japan with at present 6 stations and the California FC Partnership with in total 5 refueling station outlets. California as a region has 10 refueling outlets. Beyond these figures only California, the USA, Japan and Canada have announced more concrete plans for the extension of refueling station infrastructure so far.

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[3] Assumptions: 12,000 km driving distance per year, 0.31 kWh/km hydrogen fuel consumption.

Table 1-3: Worldwide Hydrogen Refuelling Station Demonstration Projects; numbers in parenthesis include dismantled stations

Project	CGH_2	LH_2	$LCGH_2$	Total
European Stations in Total	16	5 (8)	6	27
American Stations in Total	14 (15)	4 (7)	4 (6)	22
Asian Stations in Total	14	2	1	18
Australian Stations in Total	1			1
African Stations in Total	1			1
Total	46 (47)	11 (17)	11 (13)	68

Hydrogen can be provided to filling stations mainly in four different ways: either via LH_2 or CGH_2 trailers, via onsite generation through natural gas reforming or electrolysis of water, or via pipeline delivery. Trailer and pipeline delivery are supply methods comparable to today's supply pathways for liquid fuel or CNG stations. Onsite generation are new variants which make use of existing infrastructures such as natural gas and electricity grids.

LH_2 supply basically copies today's supply structures as it delivers the fuel from a centralized production site, the liquefier, usually adjacent to the hydrogen production plant, typically a natural gas reformer. Onsite generation of hydrogen fuel allows for a completely new fuel supply pathway which does not require access to any 'upstream business' as today for hydrocarbon fuels. Any 'independent fuel provider' can purchase natural gas or electricity as basic inputs for hydrogen production and dispense hydrogen to its clients. This opens the sector for new players and provides new business opportunities.

1.7.1 Compressed gaseous hydrogen filling stations

For present pressurized composite materials storage tanks (35 and 70 MPa) as well as for presently foreseeable storage alternatives such as alanates and cryo-adsorption, the maximum delivery pressures are determined by composite materials storage tank pressures lying in the order of 45 and 88 MPa, respectively.

These pressure levels can be achieved by different ways depending on the supply method. In the case of LH_2 supply the liquid hydrogen can be compressed by a submerged cryogenic pump, evaporized and dispensed as cold gas directly at 70 MPa. For all other supply pathways (onsite production or pipeline delivery) the gaseous hydrogen has to be compressed by compressors. For 35 MPa onboard storage filling by pressure differential from a 45 MPa onsite storage is possible. For 70 MPa onboard storage from 30 or 45 MPa onsite storage pressure booster pressurization to 88 MPa for temperature compensation is needed. Refueling times in the order of 3 minutes can be achieved also for the 70 MPa case.

Refueling interfaces for the most common supply pressures are already on the way to be standardized, presently first by the US SAE J2600 and in future also as ISO standard.

The hydrogen specific equipment costs of a refueling station lie in the order of between 0.5 million Euro up to 1.5 million Euro, depending on the capacity of the station and the technology, be it CGH_2, LH_2, $LCGH_2$ or combined refueling of $LCGH_2$ and LH_2.

1.7.2 Liquid hydrogen filling stations

LH_2 is delivered in trailers/ containers to the filling station and stored onsite either in the transport containers or in cylindrical stationary storages (vertically above ground, horizontally buried underground). With a submerged cryogenic pump LH_2 is transferred to the vehicle tank in not more than 3 minutes for a typical passenger car tank of 100-140 l. With so-called clean break coupling refueling with minimal to zero losses and subsequent refueling of vehicles without interruption has become feasible. The most advanced and most widely used coupling design comes from Linde. The only other design has been developed by Messer.

LH_2 refueling can be achieved either by fully robotized refueling interfaces or with manual refueling interfaces which are semi-automatically assisted (e.g. by a pneumatical closing of the nozzle to the receptacle of the vehicle). The existing cryogenic ball valve clean break couplings are resdesigned for easier handling, smaller diameter and lower weight. The dimensions and weight will be comparable to today's most advanced CNG and gasoline refueling nozzles.

The hydrogen specific equipment costs of a refueling station lie in the order of between 0.5 and 1 million Euro depending on the capacity of the station and the technology, be it with assisted manual or with robotized refueling interface technology.

1.7.3 $LCGH_2$ filling stations

In the case of $LCGH_2$, LH_2 is supplied and compressed by a submerged cryogenic pump, evaporized and dispensed as cold gas directly at the required storage pressure of up to 70 MPa. As cryogenic gas is being used for refueling a temperature compensation is not required through over-pressurization as necessary in case of CGH_2 refueling. $LCGH_2$ refueling for CGH_2 vehicles is always the preferred method when LH_2 has to be dispensed at a filling station and also CGH_2 will be requested.

As high pressure CGH_2 refueling processes have been advanced significantly during the last years, $LCGH_2$ refueling or even cryogenic cooling of CGH_2 at the level of liquid nitrogen (77 K) will not be a prerequisite for fast CGH_2 refueling anymore.

1.8 Hydrogen use in transport

Table 1-4 gives an overview of the applicability of the different hydrogen use technologies to the various transport modes.

Table 1-4: Overview of applicability of hydrogen use technologies to transport modes.

	CGH_2	LH_2	PEM	SOFC	AFC	H_2-ICE	H_2-GT	H_2-SIGT
Car/ van/ bus propulsion	+	+	+		Niche	+	-	-
Long-haul truck	-	(±)	+		-	(+)	-	-
Car/ van/ bus/ truck APU	(±)	(±)	+	+	-	-	-	-
Small vehicle (scooter, bike, NEV etc.)	+	-	+		(+)	+	-	-
Tramway/ regional train	+	+	+		-	(+)	-	-
Boat/ small ship	+	±	+		+	+	-	-
Large ship	-	(+)	(+)	(+)	-	+	(+)	+
Ship APU	(±)	+	+	+	(-)	(-)	(-)	-
Small airplane	(+)	+	(+)	-	-	(+)	+	-
Large airplane	-	+	(-)	-	-	-	+	-
Airplane APU	(-)	+	+	+	-	-	+	-

+ applicable, - not applicable, ± applicable under specific circumstances;
parenthesis indicate that the assessment is preliminary and requires validation through feasibility studies or prototypes.

1.8.1 Fuel cells

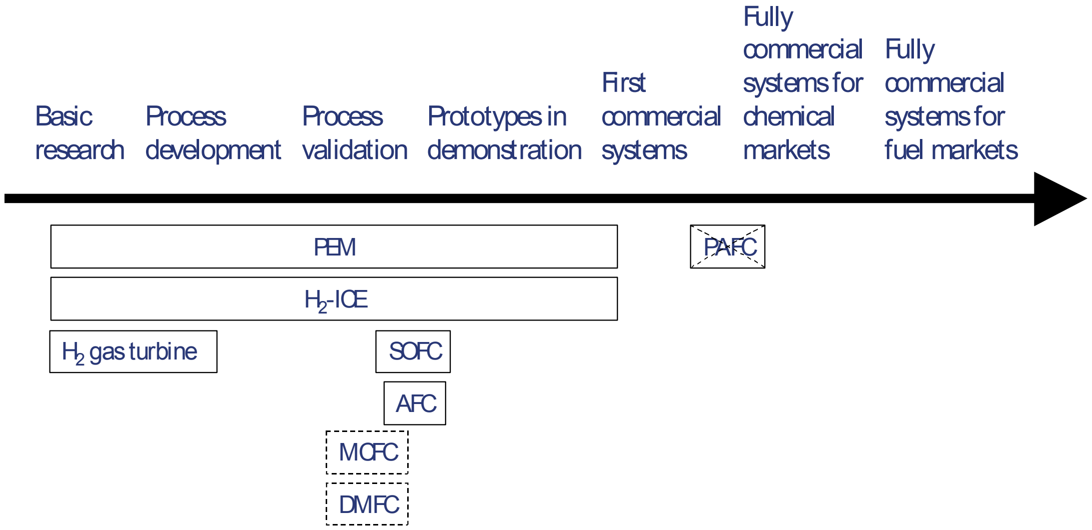
In principle, fuel cells are applicable to all transport modes.

For road vehicle propulsion, development efforts focus on PEM fuel cells. For use as auxiliary power units (APU) for cars and trucks PEMFC and SOFC are under development. AFC are suitable for niche applications.

For tramways and trains, PEMFC are considered in first development activities.

For boats and small ships, PEMFC and AFC are being considered. It is unclear whether fuel cells offer great advantages for large ship propulsion. Conventional ship engines are very efficient; only SOFC in combination with gas turbines promise higher efficiencies. MCFC and PEMFC are considered for military ship propulsion applications because of tactical benefits; it is unclear why SOFC are not considered here. Fuel cells may become attractive for ship propulsion through greatly reduced pollutant emissions and by enabling the use of alternative fuels not based on mineral oil.

Figure 1-7: Status of hydrogen fuel cell technologies; MCFC and DMFC are included for completeness, PAFC technology has been given up commercially.



For aircraft propulsion, further advancements in power density by weight are required. Nonetheless, there are first development efforts for small PEMFC planes, and studies on large PEMFC passenger aircraft. Development is being carried out on fuel cell APUs using PEM and possibly SOFC technology.

Figure 1-7 gives a qualitative assessment of the present status of hydrogen fuel cell technologies.

1.8.1.1 Alkaline fuel cell (AFC)

Alkaline fuel cells (AFC) have been used in the early space programs. AFCs are low temperature fuel cells achieving high efficiencies. Because of the alkaline nature of the electrolyte non-noble metal catalysts are suitable.

Compared to PEM fuel cells requiring noble metal catalysts AFCs are relatively cheap to produce already in small series production. On the other hand, they have lower power densities. AFCs are very sensitive to CO_2 and CO poisoning of the electrolyte. Therefore, CO_2 must be removed from reaction air increasing the complexity of the system.

Fixed electrolyte concepts have the disadvantage that CO_2 removal from the reaction air must be extremely effective as poisoned electrolyte cannot be removed from the system except by disassembling. Electrolyte circulation on the other hand causes problems regarding system design, complexity and especially electrolyte loop tightness. Most developments favor electrolyte circulation at present.

AFC is developed by only a few companies and research institutions world-wide with limited financial resources.

AFCs are not suitable for the passenger car mass market. On the other hand they are suitable for early niche market applications where the performance requirements, especially for power density, are not so stringent and where AFCs benefit from low cost small series production.

AFCs are zero emission appliances emitting only water vapor.

1.8.1.2 Proton exchange membrane fuel cell (PEMFC)

Pioneered by Ballard Power Systems of Canada, PEM fuel cells have been developed for terrestrial applications starting in the late 1980ies after a major technical breakthrough in the reduction of platinum load by Los Alamos National Laboratories, USA.

PEM fuel cells have been developed by the automotive industry worldwide, and by small start-up companies receiving significant financing through development contracts from the defense sector.

Because of its intrinsic, structural simplicity PEM fuel cells promise to be cheaper in mass manufacturing than internal combustion engines. Present cost goals for entire PEMFC propulsion systems for passenger cars are slightly higher than for ICEs. It is the goal of car manufacturers to offer PEMFC cars for prices comparable to diesel cars.

To achieve the cost goals, platinum load has to be reduced significantly from today's levels. Platinum quantities of some grams per car comparable to catalytic converters have to be achieved. If this cannot be achieved, large scale market introduction will not take place in the car sector.

At present, PEM fuel cells are manufactured by hand in very small numbers. Therefore, present costs have no relevance for a commercial market with mass manufacturing.

PEM fuel cells require hydrogen with very low quantities of carbon monoxide (CO). For transport applications, this is ideally achieved by storing pure hydrogen onboard the vehicle. For some large applications such as large ships reforming of other fuels (sulfur-free diesel/ synfuels, natural gas etc.) may be advantageous.

There are no major safety risks associated with fuel cells themselves. Risk potentials are the presence of small amounts of hydrogen and oxygen in combination with electricity, and the combination of electricity with water (for cooling). The major safety risks are associated with the fuel storage and supply to the fuel cell.

Fuel cells are a surface related technology, while ICEs are volume related. This means that fuel cell size and costs scale linearly with power (size and costs per kW of power are constant independent of rated power), while the power related specific size and costs of ICEs decrease with increasing power. The efficiency of fuel cells is ideally independent of rated power, while the efficiency of ICEs increases with rated power.

As a consequence, very large ship engines have efficiencies comparable or even higher than fuel cells, and they have reduced space requirements.

PEM fuel cells are suitable for road vehicles, tramways and regional trains, boats and small ships. It is unclear at present in how far they are suitable for large ships, long-distance high speed trains and large aircraft. They might demonstrate their suitability for small planes in first development projects started recently. Suitability for long-haul trucks depends on a suitable fuel storage.

PEM fuel cell systems have higher efficiencies (hydrogen to electricity to mechanical power) than internal combustion engines (hydrocarbon fuel to mechanical power), especially in part load operation. In most road vehicle applications this is a major advantage as propulsion systems are rarely operated at rated power. In other applications (e.g. ships, trains) which mainly operate at rated power the efficiency advantage is reduced. Very large ship engines may even have higher efficiencies than the fuel cell as thermodynamic machines increase in efficiency with increasing size.

PEM fuel cells fuelled with hydrogen are true zero emission systems emitting only water vapor. Their environmental performance depends on the pollutant and GHG emissions in fuel production and supply.

First studies indicate that PEM fuel cell manufacturing requires higher amounts of energy than ICE manufacturing being up to double as high for PEMFC cars than for conventional cars. These values have to be regarded as preliminary as mass manufacturing techniques are an important development of the coming years. In addition, the amount of platinum in a PEMFC has a major influence on cumulated energy requirements. For economic and availability reasons the platinum load has to be reduced significantly for mass manufacturing.

The cumulated GHG emissions for the production of conventional cars is around 10% of the overall GHG emissions over the entire lifetime of the car. Studies for future PEMFC cars come to different results. Cumulated energy requirements for H_2-PEMFC car manufacturing are 10% to 60% higher than for diesel ICE cars. GHG emissions are up to 100% higher. Even if cumulated GHG emissions of PEMFC car manufacturing are assumed to be double as high as for conventional cars, overall GHG emissions reductions of over 80% can be achieved with fuel cell cars operated with renewable hydrogen.

1.8.1.3 Solid oxide fuel cell (SOFC)

SOFCs are in the stage of development with a few early commercialization activities including the development and implementation of manufacturing technologies. Developments focus on stationary applications and on auxiliary power units for cars and trucks.

SOFCs can be operated on pure hydrogen, on reformate gas (mixture of hydrogen, carbon monoxide, carbon dioxide and methane depending on reforming technology and fuel used) and on hydrocarbons, which are reformed internally. Fuels have to be essentially sulfur-free. At present, SOFC systems are being developed for operation with fossil fuels, especially natural gas. These systems include components and designs that are not required for operation with pure hydrogen, e.g. sulfur removal, reforming etc.

Cost reductions are attempted to be achieved by reducing operating temperature to 700-900°C in order to allow for the use of relatively cheap metallic materials for support structures instead of ceramics. First promising results have been achieved.

In basic research, advanced SOFC concepts (IT-SOFC – intermediate temperature SOFC) attempt to achieve operating temperatures down to 400°C requiring the use of new materials for electrolyte and electrodes. Further reductions in structural material requirements and costs are expected with lower temperatures.

On the other hand, high operating temperatures allow for the internal reforming of hydrocarbons.

With present technology, SOFC are not able to follow dynamic load changes quickly, and they have rather long start-up times. Different materials used and fragile components in the cell sensitive to thermal stress require low temperature gradients. Therefore SOFCs are not suitable for applications where dynamic load changes are frequent as e.g. in road vehicles.

SOFCs are suitable as APUs for passenger cars as start-up times of several minutes are acceptable. SOFC APUs only partly replace batteries, but fully replace current electricity generators in cars with very low efficiencies of 18-22%. Current SOFC APU developments have operating temperatures around 800°C using metallic materials; ceramic structural materials would not withstand typical accelerations up to 40 g in cars.

An SOFC fueled with pure hydrogen is a zero emissions appliance emitting only water vapor. Fueled with natural gas, SOFCs emit very small amounts of pollutants (CO, NO_x, hydrocarbons). These quantities are very much smaller than those of natural gas fueled combined cycle power plants, and they are much smaller than the emissions of supplying natural gas to the plant.

1.8.1.4 Molten carbonate fuel cell (MCFC)

Molten carbonate fuel cells are not able to operate on pure hydrogen and are therefore not covered in detail here. They require a carbon containing fuel. MCFCs allow for internal reforming of methane (natural gas, biogas) or other hydrocarbon fuels.

MCFCs are developed by three industrial groups world-wide: MTU (Germany), the MOLCARE initiative (Spain-Italy) and Fuel Cell Energy (USA). First systems are commercially available in the 250 kW power range at high prices competitive only in very limited niche markets. Further technical improvements and series production are required in order to become competitive in larger markets for combined heat and power production.

1.8.1.5 Phosphoric acid fuel cell (PAFC)

Development of phosphoric acid fuel cells has been ended world-wide. The only company offering PAFC commercially, UTC fuel cells (USA), has recently decided to focus entirely on PEMFC.

1.8.1.6 Direct methanol fuel cell (DMFC)

Direct methanol fuel cells operate on methanol and are therefore not covered in detail here.

DMFCs are similar in concept, technology and materials to PEM fuel cells. Compared to hydrogen powered PEM fuel cells they suffer from a penalty in power density in the order of a factor three to four.

DMFCs are mainly developed for small portable applications.

1.8.2 Internal combustion engines

The cost goal for hydrogen internal combustion engines (ICE) passenger cars is a maximum 10% additional costs. At present, cars are hand-crafted prototypes with associated prohibitive costs. The hydrogen ICE will have some additional components, especially in the injection system. Overall, the costs of mass manufactured (>50,000 engines per year) hydrogen ICEs will be comparable or only slightly higher than those of mass manufactured common rail direct injection diesel engines. The fuel storage and supply part will incur more additional costs compared to the conventional components for liquid hydrocarbons. The main driver for cost reductions will be the economies of number in a mass market introduction.

Filling station infrastructure requirements of hydrogen ICE cars are reduced as long as they have bi-fuel engines additionally running on gasoline. Bi-fuel vehicles are not optimized for efficiency and emissions, and have higher production costs. Therefore, mass market introduction will occur with dedicated mono-fuel hydrogen vehicles. An important aspect of mass market introduction of hydrogen cars (both ICE and fuel cell) are standardized receptacle-nozzle interfaces for CGH_2 and LH_2.

The support infrastructure for maintenance and repair of hydrogen cars is another important issue requiring dedicated tools and qualified personnel at the workshops. All car companies having communicated market introduction strategies for hydrogen ICE or fuel cell vehicles (BMW, General Motors, Honda, Toyota) are already dealing with this.

Safety risks in the use of hydrogen are mainly attributed to the hydrogen storage and supply to the engine, not to the engine itself.

All types of hydrogen storage tank systems have a much higher structural stability than conventional fuel tanks. Therefore, the risk of fuel release in case of accidents is significantly reduced. On the other hand, released hydrogen has a higher potential for damage. At open air, this results in a reduced risk. In confined and semi-confined surroundings (tunnels, garages, street canyons etc.) the resulting risk potential may be higher than for conventional fuels. Theoretical and practical experimental work deals with these issues. Results will influence the design of hydrogen storage tank technology and safety concepts for hydrogen vehicles.

Hydrogen ICEs are applicable to road vehicles, trains, and ships.

NO_x emissions of lean-burn hydrogen ICEs for road vehicles are very low. Engine development aims at improving the efficiency and performance of ICE engines while maintaining their excellent emission characteristics of lowest NO_x values and almost avoiding all other emissions completely. Exhaust gas recirculation and operation of the engine with air excess via forced aspiration and intercooling are effective means of avoiding internal zones at unacceptably high temperatures, with the associated mechanisms that lead to the formation of oxides of nitrogen. The emission limits of Euro IV can be fulfilled without any after treatment measures. ZEV or SuperULEV requirements can be met by exhaust gas recirculation, heated NO_x storage catalyst or three way catalyst for $\lambda = 1$ operation, HC adsorption and only as mono-fuel hydrogen vehicle.

Hydrogen ICEs may achieve fuel consumptions comparable to diesel engines. Over the New European Driving Cycle, fuel cell vehicles consume more than 40% less fuel than advanced diesel ICEs.

1.8.3 Gas turbines

There have been several attempts to develop gas turbine propulsion systems using conventional fuels for road vehicles, none of which has reached a stage of actual commercialization. There is no development of hydrogen powered gas turbines for road vehicles.

Gas turbines have been developed for gas turbine electric train propulsions. This has been given up as diesel ICEs are more energy efficient.

Kerosene powered gas turbines are used for aircraft propulsion, where they are the standard propulsion system for large aircraft increasingly gaining market shares in smaller, regional aircraft. There have been a few development projects for hydrogen gas turbine powered aircraft.

Ships are mostly powered by large internal combustion engines, some by steam turbines. Only a few ships use gas turbines for propulsion. Gas turbines are less energy efficient than ICEs or steam turbines, but require less space. Especially in cruise ships, the reduced space requirements allow to include some more cabins, which compensates, at least partly, for the higher fuel consumption. As hydrogen storage requires more space than conventional fuel bunkers onboard the ship, hydrogen powered gas turbines make no sense in ships. Ships could also be powered by steam injection gas turbines (SIGT), which are used in stationary applications at present.

In spite of long development and aircraft utilization cycles in the order of several decades[4] no major development efforts for hydrogen aircraft have been made so far. Only theoretical work on aircraft configurations, systems and components, propulsion, safety, environmental compatibility, fuel sources and infrastructure as well as transition scenarios has been carried out in the Cryoplane project [Cryoplane 2003].

One of the reasons for this is the fact that aircraft fuels for commercial aviation are generally exempt of taxes. Hydrogen would increase the fuel costs, which form, at least for intercontinental flights, a significant share of the overall costs.

Also in international shipping fuels are exempt of any taxes. Ships burn the residues of refineries, which makes heavy fuel oil for ship propulsion the cheapest of all transport fuels. Activities for introducing minimal fuel quality standards on an international level are laborious. An inter-

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[4] The development of a large passenger aircraft takes about one decade. This plane is then sold and used for several decades. There are around 50 years between the first development efforts and the decommissioning of the last plane of one type.

national convention for limiting the sulfur content of heavy fuel oil to 4.5% (45,000 ppm compared to 50 ppm for car diesel at present in the EU) has been in the process of ratification for more than five years. Within the EU, a directive is being developed at present setting more stringent sulfur levels. Heavy fuel oil prices are around 100 $/t for an average sulfur content of 3.5% in the EU. The price premium of 1.5% sulfur heavy fuel oil is estimated to be between 45 and 80 $/t for a 100% replacement of present heavy fuel oil production in European refineries. This shows that setting (minimum) environmental standards enhances the competitiveness of hydrogen.

In addition to sulfur emissions caused by using heavy fuel oil, particulate emissions, NO_x emissions and emissions of heavy metals are also significant. Especially in the Baltic Sea and the North Sea including the English Channel, levels of air pollutants caused by ships are exceeding acceptable levels requiring legal action by the European Commission as discussed above. Emissions associated to hydrogen use in ICEs are NO_x emissions, and the emissions in the hydrogen production and supply processes.

1.9 Literature

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2 ANALYSIS OF CURRENT RESEARCH ACTIVITIES IN THE FIELD OF HYDROGEN AND FUEL CELLS

The industrial interest in hydrogen fuel is mainly triggered by the development of fuel cells, especially the development of PEM fuel cells for passenger cars.

The last decade has seen increasing research and development efforts on PEM fuel cells for automotive, stationary and portable applications. Major technical advancements have been achieved.

A major fuel cell development trend is the development of materials, components and designs of medium temperature PEMFC. In addition, research and development aims at reducing platinum load to commercially viable levels, and at increasing the lifetime of PEMFC stacks.

These research trends are complemented by an important stride towards commercialization and mass manufacturing.

Hydrogen fuel offering a very large number of possible production and supply routes requires commercialization efforts rather than basic research for a number of technologies such as on-site electrolysis. Some hydrogen production technologies such as decentralized natural gas reforming, biomass gasification etc. require further R&D efforts for commercialization, others are still in basic research. A major remaining issue of basic research and development is hydrogen storage.

Hydrogen production and supply technologies will mainly improve in economic parameters, while technical parameters have already reached rather high levels for many technologies. Improvements in hydrogen storage technologies will lead to further gradual increases of storage density and may lead to new storage concepts such as cryo-adsorption to carbon structures, or alanates.

Fuel cells will see both major technical and economic advancements. Technical advancements are necessary to achieve technical requirements such as lifetime, and to come to technical designs that can meet cost goals in mass manufacturing.

Fuel cell propulsion has the technical and economic potential to replace most of the existing propulsion technologies in most transport applications.

Fuel cells are ideally suited for using hydrogen, which in turn allows for a diversification of fuel supply options in transport, including opening the transport sector to renewable energies.

Decreasing costs of renewable energies through learning curve effects and through economies of scale and of number will be complemented by increasing prices of fossil energies due to diminishing resources. Policies for climate protection, for local air quality improvements and for an increased security of energy supply will additionally support the introduction of hydrogen. The combination of these factors will create increasing economic and commercial potentials for hydrogen and fuel cells in transportation.

Ultimately, hydrogen has the potential to replace all fossil fuels, and fuel cells have the potential to replace most other propulsion technologies.

The main trends and recent research results in the field of hydrogen and fuel cells as well as the possible improvements and future potentials are analyzed for all applications and for all timeframes.

The following table summarizes the aspects covered in this chapter. Main trends and recent research results, possible improvements of the technologies and future technical, economic and commercial potentials are analyzed for all applications in transport and for all timeframes.

Table 2-1: Analysis matrix of chapter 2.

Main trends Recent research results Possible improvements Projections for potential (technical, economic, commercial)	⊗	All applications All timeframes

The aspects covered are dealt with in general in chapters 2.1, 2.2, 2.3, while the single steps in the hydrogen pathway are analyzed in detail thereafter in chapters 2.4 to 2.8.

If not specified otherwise, the results presented represent LBST analyses.

2.1 Main trends and recent research results

The industrial interest in hydrogen fuel is mainly triggered by the development of fuel cells. Especially the development of PEM fuel cells for passenger cars promises large commercial potentials.

The last decade has seen increasing research and development efforts on PEM fuel cells for automotive, stationary and portable applications. Major technical advancements have been achieved by small start-up companies and large car manufacturers. Power densities of PEMFC stacks have increased by more than a factor of 10, fuel efficiencies of prototype fuel cell cars already significantly exceed those of advanced diesel cars.

A major fuel cell development trend is the development of materials, components and designs of medium temperature PEMFC. In addition, research and development aims at reducing platinum load to commercially viable levels, and at increasing the lifetime of PEMFC stacks.

These research trends are complemented by an important stride towards commercialization and mass manufacturing.

Hydrogen fuel offering a very large number of possible production and supply routes requires commercialization efforts rather than basic research for a number of technologies such as on-site electrolysis. Some hydrogen production technologies such as decentralized natural gas reforming, biomass gasification etc. require further R&D efforts for commercialization, others are still in basic research. A major remaining issue of basic research and development is hydrogen storage. For many hydrogen technologies, a technical status has been achieved that permits commercialization, which will be accompanied by further technical advancements and economic optimization.

2.2 Possible improvements of H_2 and FC technologies

Hydrogen production and supply technologies will mainly improve in economic parameters, while technical parameters have already reached rather high levels for many technologies. Biomass gasification to hydrogen in decentralized units requires increased efforts in order to develop efficient processes achieving reliable operation and constant product gas quality. Compact onsite natural gas steam reformers have the potential of further increases in efficiency and reductions in cost.

Improvements in hydrogen storage technologies will lead to further gradual increases of storage density and may lead to new storage concepts such as cryo-adsorption to carbon structures, or alanates.

Fuel cells on the other hand will see both major technical and economic advancements. Technical advancements are necessary to achieve technical requirements such as lifetime, and to come to technical designs that can meet cost goals in mass manufacturing.

2.3 Projections for technical, economic and commercial potential

Fuel cell propulsion has the technical and economic potential to replace most of the existing propulsion technologies. Fuel cells show advantages in efficiency and emissions in most transport applications.

In addition, fuel cells are ideally suited for using hydrogen, which in turn allows for a diversification of fuel supply options in transport. This includes opening the transport sector to renewable energies, which is required by climate change and by shortages of fossil and nuclear energy resources.

Detailed analyses show that hydrogen from renewable sources can become competitive for road transport at crude oil prices only slightly higher than prices during longer periods of the last 30 years. Decreasing costs of renewable energies through learning curve effects and through economies of scale and of number will be complemented by increasing prices of fossil energies due to diminishing resources.

Policies for climate protection and for local air quality improvements will additionally increase fossil fuel prices. The combination of these three factors will create increasing economic and commercial potentials for hydrogen and fuel cells in transportation.

Ultimately, hydrogen has the potential to replace all fossil fuels, and fuel cells have the potential to replace most other propulsion technologies.

2.4 Hydrogen production

In general, large-scale hydrogen production technologies (natural gas steam reforming, electrolysis, coal and oil gasification) are well-established technologies without major development potentials. In contrast, small-scale, onsite hydrogen generation technologies (compact natural gas steam reformers, small pressurized electrolysers, biomass gesification) have been developed recently and have significant improvement potentials both economically and technically.

In hydrogen production, the main trends and recent research results are the developments of

- compact natural gas reformers for onsite hydrogen production: first prototypes are available, development continues,
- pressurized electrolysers for onsite hydrogen generation: systems are available, commercialization is on-going,
- biomass reforming systems of medium scale (2.5 to 20 MW_{th}): first test systems and prototypes are in test operation,
- large scale hydrogen production from natural gas and coal including CO_2 sequestration: one first project of CO_2 sequestration is in operation in Norway, research on possible con-

cepts has been carried out both for hydrogen and for electricity production, industrial and political interest for RD&D projects is mainly concentrated in Norway, the Netherlands, the United Kingdom, Italy and in North America.

Other hydrogen production methods of limited research efforts have shown the following results and developments recently:

- High temperature heat using thermochemical cycles recently receives increased interest in countries that favor the use of nuclear energy: several promising cycles using solar or nuclear heat have been identified (some of the work goes back to the early 1970ies), the basic chemical reactions have been verified, basic nuclear reactor designs are being identified.
- Photo-electrochemical hydrogen production: Conventional chemical methods of making and testing materials have proven to be inefficient and therefore have to be replaced by electrochemical methods of combinatorial library synthesis and screening as known from new pharmaceutical discoveries in order to increase the rate of discovery.
- By-product hydrogen: Activities for the identification of sources and quantities have been carried out.

2.4.1 Hydrogen from natural gas

The major result achieved recently in natural gas reforming is the development of first compact onsite NG reformers. Large-scale steam reforming of natural gas is a well-established industrial process without need for development and without significant further development potential.

Downscaling of existing large-scale natural gas reformers did not result in sufficiently compact and cost efficient units. Therefore, several companies (e.g. Hyradix, Hexion, Mahler, Carbotech) based on existing process technology know-how have started the bottom-up design of compact reformers (steam reforming or autothermal reforming) which shall result in efficient units with small footprint (allowing for containerized integration into refueling stations) which can be mass manufactured at competitive costs. Such improved reformers will become available for both small scale domestic (2-5 kW range) or commercial (10-100 kW) fuel cell combined heat and power installations and for small refueling stations in the 50 – 500 Nm^3/h capacity range. The timeframe for commercial introduction of first units is foreseen for around 2005 and mass manufacturing in several 10s of thousands and later 100s of thousands of units annually by 2010.

2.4.2 Hydrogen from electricity

During recent years, small pressurized electrolysers have been developed and have started to enter a commercial market for onsite hydrogen production for industrial applications.

Several companies (GHW, Norsk Hydro, Vandenborre Hydrogen Systems, Proton Energy) are working on 1-3 MPa pressurized electrolyzers with gradually improved efficiencies due to minimized auxiliary energy requirements. The advantage of pressurized hydrogen production is that the pressurization in the electrolyzer is much more energy efficient than the compression of hydrogen produced at ambient pressure to a first compression stage level (e.g. 3 MPa, compression ratio 1:30) from where it can be compressed further to filling station dispensing pressure (e.g. 45 or 88 MPa, compression ratio from 3 MPa 1:15-29).

Prototypes of these pressurized electrolyzers are already installed in several test applications. Commercial introduction for hydrogen fuel production is foreseen for the timeframe of about 2005 to 2010 latest, though continuous improvements in design and engineering will continue. Electrolysers have large cost reduction potentials through mass manufacturing.

2.4.3 Hydrogen from biomass

Some suitable process technologies for biomass gasification to hydrogen are under development by small companies with limited budgets. They are now in the phase of process development and validation. First prototype testing is underway for medium-size plants (2.5-20 MW_{th}). These have not yet demonstrated satisfactory production over longer periods. Increased development efforts are required to develop reliable and efficient process technology.

Developers are confident to have commercial units available between 2005 and 2010. H_2 production costs shall be quite low (lowest of any renewable hydrogen production technologies) and come close to those of hydrogen reformed from natural gas.

Most biomass gasification development efforts aim at producing fuel gas for combined heat and power production. These process are in general not suitable for pure hydrogen production.

2.4.4 Hydrogen from coal or from petroleum

Coal gasification processes have been developed many decades ago, but have only been installed in a few plants world-wide. During the last decade, interest has renewed with the development of Integrated Gasification Combines Cycle (IGCC) coal or heavy fuel oil power plants. First coal-fired plants in Europe have been installed in the Netherlands in 1993 and in Spain in the second half of the 1990ies. With these projects, industrial experience has been (re)gained and the gasification technology has been fine-tuned. The main technical step, though, was the development of gas turbines for use with syngas.

Some gasification units have also been installed at refineries. These transform very heavy oil fractions, so-called residues, into hydrogen for use within the refinery, or to syngas for subsequent power production (IGCC).

2.4.5 Hydrogen from fossil energy with CO_2 sequestration

2.4.5.1 CB&H process

No further developments have taken place since the installation of the first commercial plant installed in Montreal, Canada, in mid-1999. The commercial status of the technology is unclear.

2.4.5.2 CO_2 sequestration

CO_2 is being stored underground today in two major projects world-wide – one offshore Norway and the other in Canada.

The Saline Aquifer CO_2 Storage (SACS) project in Norway captures CO_2 from natural gas production at the Sleipner West field and injects it into a saline aquifer. Production from the Sleipner West gas and condensate field began in August 1996 [SACS 2000].

The Weyburn CO_2 Monitoring Project in Canada monitors the sequestration of CO_2 in a depleted oil reservoir. CO_2 is injected as part of an enhanced oil recovery project. CO_2 injection started in October 2000.

Initial results taken in the fall of 2001 show, for the most part, an orderly advance of the CO_2 out into the reservoir, along the line of the horizontal injectors. However, there is some evidence of CO_2 fingering along suspected off-pattern fractures, signaling the possibility of early CO_2 breakthrough in some locations [Weyburn 2000].

The concept both for hydrogen and electricity production receives interest from industry and politics mainly in Norway, the Netherlands, the United Kingdom and Italy as well as in North America.

2.4.6 Other hydrogen production technologies

2.4.6.1 High temperature heat using thermochemical cycles (nuclear, direct solar)

The concepts of thermochemical cycles using high temperature heat are still in the state of basic research and early process design. Activities are mainly carried out with the interest to use new nuclear reactor designs for these cycles. Main activities are carried out in France, Japan and the USA, the latter receiving increased attention lately in the framework of US-President Bush’s strong increase in hydrogen research funding. A tentative timeframe proposed by General Atomics of USA is to develop the new nuclear reactor design until 2010 and to install a nuclear hydrogen demonstration plant until 2015. In general using nuclear heat for hydrogen production is seen as a long-term option [GA 2002].

Research with the explicit background of using solar energy is carried out in Switzerland, Korea, the USA and possibly other countries.

The potential of the use of nuclear fission in general is limited by the amount of uranium available globally, which is limited just as fossil energies. Only the use of breeder technology, which has failed to prove its viability, could overcome these limitations.

2.4.6.2 Biological hydrogen production

Biological hydrogen production is in the phase of basic research. Main goal of present work is to increase the hydrogen yield. Biotechnology options receive increasing attention.

At present it is not possible to assess the potential for commercialization.

2.4.6.3 Photo-electrochemical hydrogen production

At present the structure function relationships of photocatalysts are mostly unknown. Therefore, conventional chemical methods of making and testing materials have to be replaced by electrochemical methods of combinatorial library synthesis and screening as known from new pharmaceutical discoveries in order to increase the rate of discovery. By this approach mixed metal oxides of W, Cu, Ti and Fe hosts can be identified and new electrosynthetic routes be developed and thus materials be improved.

Photo-electrochemical hydrogen production is in the phase of basic research.

At present it is not possible to assess the potential for commercialization.

2.4.6.4 By-product hydrogen

Recently, by-product hydrogen has received increased attention as an early cheap hydrogen source for the build-up of a hydrogen refueling infrastructure. In Germany about 1 billion Nm^3/a of chemical by-product hydrogen are produced which could be replaced by natural gas and made available for large-scale hydrogen demonstration activities in the mobile and stationary sector. Between 400,000 and 600,000 efficient fuel cell vehicles could be operated with these quantities in Germany [LBST 1998].

2.5 Hydrogen distribution and conditioning

2.5.1 Gaseous hydrogen transport

Over the last years 30 MPa composite materials bundle storage on trailer (MCS, Dynetek) has been developed which allows somewhat better supply efficiencies for the delivery of small hydrogen volumes in the form of CGH_2. In general, this supply mode is energetically and economically unattractive for fuel applications with the exception of early niche markets.

At present, there is only one initiative for the development of a long distance hydrogen pipeline by the Japanese initiated International Hydrogen Pipeline Forum. It shall extend from Russia via China to Japan and transport natural gas first and pure hydrogen later-on. There are first initiatives to develop regional hydrogen pipeline networks supplying chemical by-product hydrogen to various consumers (e.g. residential fuel cells, transport).

First studies on admixtures of hydrogen to natural gas and on the use of natural gas distribution grids for pure hydrogen have been carried out several years ago, and first RD&D projects on industrial level are being started at present.

2.5.2 Hydrogen liquefaction

Conventional liquefiers have large improvement potentials without the need for technological breakthroughs. Many advanced concepts have been developed in the 1960ies and 1970ies, but have not been implemented because of slightly higher investment costs. Lower energy consumption and reduced space requirements have not been interesting goals for industry [GM-WTW 2002].

Several companies have the know-how to design and manufacture hydrogen liquefiers: Air Products (USA), Air Liquide (France), Linde (Germany), Praxair (USA) and Iwatani (Japan). With presently existing components plants with 150 t/d capacity can probably be built without major development efforts as one-train plants even though the next plants would rather not be larger than 60 t/d. The limiting factors for plant size are the heat exchangers. On the one hand, they have to be manufactured using existing brazing furnaces with given size limitations. On the other hand, the size is limited by the possibility to transport the heat exchangers from the manufacturing plant to the liquefier location.

Larger capacities than 150 t/d would have to be realized in modular form consisting of several plants or development efforts into larger capacities would have to be invested. In the Japanese WE-NET project a design study for a very large plant of 300 t/d has been undertaken [WE-NET 1997]. The specific energy efficiency (electric energy input/ thermal energy in LH_2) of small to medium plants of between 0.3 and 0.36 can be lowered to between 0.23 and 0.29 depending on size and H_2 input pressure without any change in process and technology. In case magneto-caloric refrigeration will demonstrate its viability one day in large-scale plants (nitrogen pre-cooling + 2-3 magneto-caloric liquefaction cycles) significant efficiency improvements of a factor of 1.3 – 1.5 could be obtained in comparison to today’s best obtainable thermodynamic Carnot efficiencies of 40%.

It is not clear at present if magneto-caloric refrigeration will make it one day to cost effective, efficient and commercial scale technology. At present only first steps into small-scale natural gas liquefaction are being undertaken with very few prototype developments.

2.6 Onboard hydrogen storage

2.6.1 Status of commercialization

Compressed storage devices up to 35 MPa are already commercially available, even though CGH_2 storage vessels are manufactured in small numbers at present. There is considerable overlap and spin-off with natural gas storage. First 70 MPa vehicle storage tanks are available.

Liquid hydrogen storage devices are commercially available in single unit quantities. Due to missing mass production these storage devices are very expensive today.

Metal hydride storage devices are commercially available at low temperature and high cost (with up to 1.8% by weight storage density). Their costs are mainly determined by the material cost.

Small chemical hydride storage systems (boron hydride) are already commercially available, though at high cost and low quantities.

Novel material storage systems such as activated carbon or novel medium temperature hydrides are being developed and are not yet commercially available.

2.6.2 Recent research results

Onboard hydrogen storage development has received a strong push during the last two to three years. Development efforts have been multiplied. This is due to a growing number of hydrogen vehicle developments (mainly fuel cell cars). In addition, car manufacturers developing fuel cell vehicles have realized that hydrogen is the most promising fuel choice for fuel cell cars (gasoline reforming is technically not feasible, other potential fuels such as methanol do not show enough potential for production from renewable energies to justify their market introduction).

Table 2-2 summarizes the present status of onboard hydrogen storage.

Within a few years only, CGH_2 storage pressures have been increased from 20 MPa to 70 MPa with first systems approved for cars.

In LH_2 storage, holding times (dormancy) have been extended from 4-5 days to 12 days through the development of a cryogenic air cooled LH_2 storage tank. Cold gaseous hydrogen extracted from the LH_2 tank exchanges its ‘cold potential’ during heating up via heat exchanger to air sucked in and cooled down to –191°C where it liquefies. This flows through a thermo-jacket surrounding the insulation of the inner tank serving as additional 'refrigerator'.

Activated carbon storage at 80K and 3.5 MPa has achieved storage densities of up to 10% by weight. Results at room temperature which promise storage densities above 1% by weight are not yet proven by independent laboratories and are still questionable, though their validity cannot be ruled out.

2.6.3 Main trends and possible improvements

There are two main trends in onboard hydrogen storage development: Step by step improvement and optimization of CGH_2 and LH_2 storage working on all components, and basic research and development of novel storage concepts such as cryo-adsorption at carbon materials and advanced metal hydrides/ alanates.

Thus far, no results have been achieved indicating that storage densities higher than those of liquid hydrogen storage systems can be achieved. Nonetheless, this can never be ruled out. Table 2-2 summarizes the present status and the development goals of onboard hydrogen storage.

In CGH_2 storage, materials questions are being tackled, especially for the liner, but also for the fibre and resin materials. Also the integration of the metallic or plastic liner and of the fibers into the boss of the storage cylinder is an important aspect of present development efforts. Quality control in manufacturing is an important issue.

In LH_2 storage, improvement of boil-off times by recuperation of cooling energy during hydrogen withdrawal is an important subject of development. Improved insulating materials and designs to be used for mass production and cost reduction are being developed.

In metal hydrides/ alanates, nanostructering of materials in order to reduce reaction kinetics (fueling times) is an important issue of development. Additionally, the reduction of temperature levels from 200°C towards 150-100°C at constant storage densities is an important research goal. A systematic analysis and selection of most promising alanates is being carried out. Alanates promise to achieve similar storage densities as 70 MPa CGH_2 (or even better) at reduced safety concerns.

Table 2-2: Typical data for different hydrogen storage systems including containment; values are approximate and may vary for different system configurations.

storage type	technical data			parameters	goals
	kWh/l	kWh/kg	%-wt		
Compressed storage	0.6 1.0	1.8 1.8	5.4 5.4	p=35 MPa p=70 MPa	p=70 MPa weight reduction
liquid storage	1.5	3.5	10.5	T=20 K; 5 days dormancy	reduce boil off/ longer dormancy, flexible geometry
metal hydride (Ti, V alloys)	1.1	0.4	1.2	T<80 °C, p<3 MPa	Niche applications in transport only
nanostructured metal hydride	1.0	1.1	3.4	T>150 °C	fast dynamics
alanates	1.0	1.1	3.4	T~150 °C	stability, low T, higher storage density
boron hydride	1.0	1.2	3.7	-	-
activated carbon	1.0	1.4	4.2	T~80 K, p=4 MPa	improved materials, higher storage density

In carbon materials storage, improved materials with higher adsorption energies allowing for higher storage temperatures (above 80 K) and large specific inner surface areas are being sought. Cryo-adsorption promises to achieve LH_2 storage densities at very much longer holding times before boil-off.

The recycling processes of boron-based chemical hydrides ($NaBO_2$ either indirectly to $C_3H_9BO_3$ or directly to $NaBH_4$) are subject of research and development.

Borazane BH_3-NH_3 also is a stable and transportable solid of low specific weight. It is under investigation as hydrogen storage material of high potential.

2.7 Hydrogen filling stations

2.7.1 CGH_2 filling stations

70 MPa refueling technology (Powertech, Linde etc.) including compression has been developed in recent years [HyWeb 2003]. Major improvements are on the way regarding standardization of the coupling/ receptacle by SAE in the draft standard J2600 which later-on will also be reflected in a widely identical ISO standard. Also the standardization of the refueling proto-

col (SAE J2601) is on its way [EIHP 2003]. These are key elements ensuring that only one design for the nozzle/ receptacle will be used worldwide in order to refuel CGH_2 vehicles (a level of achievement which has not been achieved for CNG vehicles so far). Also optimization efforts with regard to the refueling procedure are under way which will allow the refueling of a standard vehicle tank of e.g. 100 l within not more than 3 minutes without overheating the composite materials in the pressure container.

Significant progress has been made during the last few years and prospects look promising that 70 MPa-refueling technology will be proven and commercial as soon as mass introduction of the first fuel cell vehicles will start by the end of this decade.

2.7.2 LH_2 filling stations

In the last years robotized and semi-automatic LH_2 refueling technologies with clean brake coupling have been developed (by Linde) [h2cars 2003]. The diameters and the design for easy handling are presently under development. Also submerged LH_2 pumps are in development and testing in order to allow for continuously repeated (near) zero loss refueling of LH_2 vehicles in less than 3 minutes per refueling action.

LH_2 refueling interfaces have achieved significant progress since about 1995. In order to come to efficient and cost effective filling technology cryogenic pumps have to improve their lifetime and availability and also have to achieve cost reduction goals.

2.7.3 Other filling stations

Air Products has developed a mobile containerized refueling system based on liquid hydrogen delivery for the refueling of the first U31 (212A class) submarine prototype, which stores hydrogen in metal hydride storage tanks. Presently the unit undergoes practical testing.

2.8 Hydrogen use in transport

2.8.1 Fuel cells

2.8.1.1 Alkaline fuel cell (AFC)

During recent years there have been a few attempts to commercialize AFC technology.

Commercialization of AFCs failed in 2001 as Zetek Power of Belgium and the UK went bankrupt. The assets have been taken by Eident Energy of Belgium aiming at a continuation of the development.

Very recently, Astris Transportation Systems (ATSI) has been formed in Montreal, Quebec, Canada as the operating entity of a fuel cell development and production joint venture established by Astris Energi and CareAction, both of Canada. ATSI will soon initiate the installation of the world's first automated facility for mass production of alkaline fuel cell systems of Astris design according to a company press release. AFCs will power a variety of small vehicles, e.g. for the disabled and seniors.

Independent Power Technologies, a Russian company, has recently introduced an industrial prototype of a 6 kW AFC generator suitable for mass production according to a company press release. The company is looking for western partners for the commercialization of the product.

The main research trends are the following:

New stack designs are being developed with circulating electrolyte suitable for removal of carbonate, which develops through electrolyte poisoning with CO_2. AFCs for space and submarine applications had fixed electrolytes optimized for operation with pure oxygen. A major area of stack development is the improvement of electrolyte tightness of AFC stacks, e.g. by the so-called “monoblock” concept.

Dedicated CO_2 scrubbing technologies are under development for air input from existing technologies for industrial applications.

In addition, research efforts are made to increase the CO_2 tolerance of AFC stacks.

A major point in cost reduction efforts is the replacement of currently used noble metal electrocatalysts by non-noble metal catalysts.

On the systems level, systems for portable applications are under development in addition to the existing developments for mobile and stationary applications.

The commercial potential of AFCs is difficult to assess. Several niche markets are being targeted. Reliable information on cost reduction potentials are scarce. Only few industrial activities are existing world-wide, the success of which remains to be seen.

2.8.1.2 Proton exchange membrane fuel cell (PEMFC)

There are two major development trends in PEM fuel cells: On the one hand basic materials research and development including medium temperature membranes (100-200°C) and metallic bipolar plates is carried out. On the other hand major efforts are made in system integration of PEMFC stacks into systems and of PEM systems into the applications.

The development of medium temperature membranes promises significant reductions in system complexity e.g. by not requiring humidification and by reduced sizes of cooling components. Medium temperature membranes not requiring humidification would also greatly increase the reliability of the stack. At present, proton conductivity depends on the water content of the membrane. “Dry” membranes or “flooded” MEAs do not operate satisfactorily. These problems would be suppressed without the need for water for membrane conductivity. Celanese of Germany is the first company to offer medium temperature membranes and MEAs operating at up to 200°C to selected customers.

Work on new membranes is also motivated by the relatively high manufacturing costs of standard Nafion membranes even at large volumes.

In addition, operating temperatures above 100°C would significantly reduce corrosion problems of metallic bipolar plates promising highest power densities and low manufacturing costs. The corrosion problems are to a significant degree caused by water in the stack requiring a very careful water management in low temperature PEMFC systems.

Bipolar plates are a major focus of development. This includes metal bipolar plates as well as improved carbon composite materials. A major achievement are improved production technologies for carbon-based bipolar plates, and increased power densities through thinner plates. Further advancements are expected. In metal bipolar plates, major advancements in corrosion resistance have been made. It is unclear whether some companies have already resolved the corrosion problem entirely. Other work focuses on electrically conductive polymer materials.

Development efforts aimed at reducing platinum load focus on adding other catalyst materials, and on developing nano-structured catalyst support materials increasing the reactive surface. The mid-term development goal is to achieve a platinum load of 0.1 mg/cm² per electrode, translating to a platinum requirement of 14 g for a 50 kW stack. Work on replacing platinum entirely has been reduced during recent years as no promising results have been achieved.

PEM fuel cells have separately achieved all major technical goals required for commercially competitive mass manufacturing for passenger cars: long lifetime, high power density and low platinum load. The major development task is to achieve these combined goals in one single stack technology.

In addition to materials and component development, mass manufacturing technologies for PEM fuel cells will be developed during the coming years.

PEM fuel cell propulsion has the potential to replace the internal combustion engine entirely in the passenger car, light duty vehicle and city bus sectors. This is one major reason for car industry to develop PEM technology. As a spin-off from car industry PEMFC may become interesting for regional trains, boats and small ships and may become an interesting alternative to catenaries for tramways. It is unclear in how far PEMFC are an interesting option for large ship propulsion as conventional ship engines are more efficient and because SOFC in combination with gas turbines promise higher efficiencies.

To achieve the cost goals, platinum load has to be reduced significantly from today’s levels. Platinum quantities of some grams per car comparable to catalytic converters have to be achieved. If this cannot be achieved, large scale market introduction will not take place in the car sector.

2.8.1.3 Solid oxide fuel cell (SOFC)

SOFC are being developed for stationary applications and for application as auxiliary power unit (APU) in passenger cars and trucks, and possibly for aircraft APUs.

In the framework of the FCSHIP project SOFC is considered for auxiliary power supply of a large passenger ferry. There are no dedicated SOFC development efforts for application in ship propulsion.

Main trend in SOFC development is the reduction of operating temperatures. The “standard” electrolyte material yttrium-stabilized zirconia (YSZ) suffers from significantly reduced electric conductivity below 800°C. For lower temperatures research and development focuses on cerium gadolinium oxide (CGO) electrolytes. In addition, material research is carried out on new electrode materials and new structural metal materials.

Temperature reduction results in the use of cheaper metal materials, less thermal stress, increased lifetime, higher dynamics and faster start-up. On the other hand, higher temperatures are required for internal reforming in case hydrocarbon fuels are used.

SOFC stack development is carried out on all three stack designs (planar, tubular, monolithic), which is unique to SOFC. Obviously, there is no common assessment of the most technically and economically promising design.

Commercialization efforts include the development of new manufacturing techniques for low-cost production of SOFC. Market entry of SOFC APUs for passenger cars is scheduled within two years.

Major advancements in materials research, stack development and manufacturing techniques are required for commercialization of SOFC technology. Achieving all technical and cost goals, SOFCs have a large potential for stationary power or combined heat and power production. To achieve these goals, SOFC technology requires increased industrial commitment.

2.8.1.4 Molten carbonate fuel cell (MCFC)

MCFC do not operate on pure hydrogen.

MCFC are mainly being developed for stationary applications. Dedicated MCFC development efforts for application in ships are limited to some military projects in the USA. Additionally, there have been studies for MCFC or PEMFC powered ships for the Dutch Navy. It is unclear whether any hardware developments are carried out.

In the framework of the FCSHIP project funded by the European Commission fuel cell propulsion and/ or auxiliary power supply is being studied for small and large ships. For the small ship PEMFC propulsion is considered, for the large ship, PEMFC, MCFC and SOFC are considered for auxiliary power supply.

2.8.1.5 Phosphoric acid fuel cell (PAFC)

Development of PAFC has been ended world-wide.

2.8.1.6 Direct methanol fuel cell (DMFC)

DMFC are not operated on hydrogen.

DMFC are mainly developed for small portable applications.

A major breakthrough in membrane technology would be necessary in order to resolve the problem of significantly reduced power density compared to hydrogen fuelled PEMFC.

2.8.2 Internal combustion engines

Over the last three decades several companies and research institutes have dedicated significant efforts to develop internal combustion engines (ICEs) for hydrogen use.

The major efforts in the automotive industry have taken place at BMW, DaimlerChrysler Mazda, Ford, and MAN, with BMW, Ford and MAN presently aiming at commercialization. DaimlerChrysler stopped all of its extensive activities in 1995 when it switched to fuel cells for hydrogen propulsion. Mazda gave up its work on the Wankel (rotary) engine in the late 1990s, whereas Ford and MAN started only in the mid-1990s. The longest experience is available at BMW which is active in engine and vehicle development since the late 1970s. BMW intends to start production and sales of a series manufacture ICE hydrogen 7-series vehicle in small numbers (some hundreds) by 2006/7.

Also, several research organizations have been active in the development of ever improved H_2-ICEs for automotive applications. Also low-effort development for ICEs in scooters has been undertaken in Germany and in India.

BMW engine development aims at improving the efficiency and performance of its H_2-ICE engines while maintaining their excellent emission characteristics of lowest NO_x values and almost avoiding all other emissions completely. BMW furthermore tries to replace inefficient auxiliary power consumers around the engine, e.g. the generator is to be replaced by a fuel cell.

Ford has performed development work on 2.0 and 2.3 l four cylinder hydrogen engines. The 2.3-liter, four-cylinder supercharged, intercooled hydrogen internal combustion engine is coupled with a hybrid electric transmission which offers enhanced fuel economy compared to the non-hybridized precursors. According to Ford the engine can reach an overall efficiency of 38 percent (best point), which is approximately 25 percent better than a gasoline engine. Since quite some time there are rumors even in the media that Ford will advance its H_2-ICE development with assistance of BMW.

MAN is on the way to develop more energy efficient hydrogen engines for buses with high pressure injection and internal mixture formation, allowing both high power outputs and low criteria pollutants, especially low NO_x emissions. MAN is presently finalizing an improved 200 kW engine concept and will undergo testing in 2004. These engine capacities are usually also suitable for light commuter trains or light passenger taxi boats on rivers or lakes.

In Canada, Westport has developed pilot injection natural gas engines for buses. Small amounts of diesel are injected into the piston starting the ignition of the natural gas without the use of spark plugs. Hydrogen engines have not yet been developed, but the concept may also be used for hydrogen combustion.

Since the 1970s Musashi Institute of Technology, Japan, has modified 10 vehicles to hydrogen operation. Musashi was the first to use high pressure injection in its engines. The pressure is generated by a submerged cryogenic LH_2 pump in the LH_2 storage tank. The LH_2 is then evaporated and injected into the engine with 9-10 MPa pressure. Besides several passenger cars Musashi has also converted two small delivery trucks using the same engine conversion design [h2cars 2003].

In cooperation with two chairs of the Technical University of Munich the well known ship diesel engine manufacturer MAN B&W Diesel AG of Augsburg, Germany, has performed development work on a direct-injecting hydrogen-diesel engine with high efficiency and low emissions. The experimental investigations and the numerical simulations show that compression ignition with direct injection of hydrogen can be realized. The realization of a compression ignition hydrogen engine requires minor modifications to the engine but significant changes to the fuel injection system. Further development and commercialization activities have not been announced.

Wärtsilä Corporation of Finland, a major ship engine manufacturer, has recently developed a pilot injection gas engine for large ships running on natural gas. Small amounts of diesel are injected starting the ignition of the natural gas in the piston. With modifications, this concept may also be applicable to hydrogen use, but there are no development efforts in this direction at Wärtsilä at present.

2.8.3 Gas turbines

An interesting possibility for future hydrogen use is in aviation using gas turbines. With passenger and aircraft miles increasing rapidly, aviation is set to become a significant source of greenhouse gas emissions. Aircraft engines burning hydrogen would still emit small amounts of NO_x (but this can be tightly controlled using lean-burn technologies) and water vapor. While water vapor is also a greenhouse gas, its effect depends on the height at which it is released.

For cruising altitudes below 11 km it has considerably less effect than the greenhouse gas emissions from similar engines operating on standard aviation kerosene; below 10 km the effect is negligible. In high altitudes, not only carbon dioxide is an important greenhouse gas, but also NO_x, water vapor, condensed water (condensation trails) and soot; NO_x and SO_2 aerosols on the other hand reduce the greenhouse effect. The net effect is still subject to some scientific uncertainty, but is certainly larger than the effect of the emitted CO_2 alone. Hydrogen used as airplane fuel would reduce the greenhouse effect of cruising, while the total effect depends on the production of hydrogen [Oeko 2003-2].

It has already been shown that it is possible to build and operate such turbines. A hydrogen aircraft would need to be re-designed to accommodate the large volumes of hydrogen required to replace the kerosene.

In 2002 a two year European study on hydrogen use in aircraft has been finalized [Cryoplane 2003]. This study was a continuation on European level of the earlier German-Russian Cryoplane research and development activities which should result in an LH_2 operated Airbus 310, or as intermediate step in a Fairchild Dornier 328 to be converted to LH_2 operation. Both development goals were not reached due to changes in the strategic orientation of the industrial partners involved. For the time being no aggressive development activities for a full hydrogen aircraft are known. Nonetheless, some activities on auxiliary power unit (APU) development for aircraft are starting.

In the framework of the EQHHPP jet engine combustor concepts were tested for optimized hydrogen operation. New combustion chamber designs with controlled combustion were evaluated. They included the lean combustion concept, the lean combustion concept with premixing, the staged rich/ lean combustion, the catalytic combustion as well as concepts with variable geometries. Each of these concepts provides the possibility to burn the feed fuel stably by avoiding local hot spots and thus to reduce nitrogen oxide emissions drastically.

Hydrogen in particular provides excellent preconditions with respect to a stable and NO_x minimized combustion due to its wide ignition range at lowest possible fuel/ air ratios which cannot be realized in the case of kerosene fuel. On this basis, low combustion temperatures are feasible and due to the high burning velocities of hydrogen (8 times that of kerosene) low residence times of the fuel/ air mixtures prevail and subsequently result in a reduced formation of NO_x.

The feasibility of lean combustion with hydrogen at very low NO_x emission levels has been proved experimentally in specially designed test rigs. Combustion chamber concepts with and without pre-mixing were analyzed.

The not pre-mixed ‘High Shear System’ showed excellent flame stability in the combustion process over the entire operating conditions. The ‘Perforated Plate Injector’ concept achieved very low NO_x emissions values, 1/20 of the legal limits for advanced kerosene jet engines. Instabilities of the flame occurred only outside the regular operating conditions.

Based on the test results from this program, low NO_x hydrogen gas turbine combustors can be achieved. The substantial NO_x emission reduction potential (by a factor of 20) of hydrogen as compared to kerosene fueled engines has a distinct environmental compatibility advantage (0.7 g NO_x/kg fuel versus 15 g NO_x/kg fuel).

2.9 Literature

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3 REVIEW OF EXISTING APPLICATIONS AND PROTOTYPES OF HYDROGEN AND FUEL CELL APPLICATIONS IN ALL TRANSPORT MODES

Hydrogen is not yet used commercially as a transport fuel.

Since 1967 some 110 different fuel cell vehicle prototypes have been developed, and some 36 different hydrogen internal combustion engine (ICE) prototypes. Several of them have been built in more than one unit, summing up to a total number of some 230 fuel cell vehicles and some 66 ICE vehicles until the first months of 2003. Most of the vehicles have been presented after 1995.

Hydrogen fuel cell cars have evolved from rolling laboratories to fully useful cars without compromise in interior or trunk space. Concept vehicles incorporating purpose design elements and ‘x-by-wire’ technologies have been presented demonstrating the conceptual possibilities of fuel cell powertrains.

For other transport modes, only hydrogen fuel cell powered submarines have been developed and will be sold to navies world-wide. Very first prototypes of fuel cell powered boats have been presented or announced. Few projects of hydrogen powered small aircraft have been announced. A first prototype of a hydrogen powered mining locomotive has been developed.

20 fleet demonstration activities of hydrogen ICE or fuel cell vehicles have been carried out or are in concrete planning at present. The first fleet demonstration project took place in Germany between 1984 and 1988 with 10 cars and delivery vans powered by hydrogen ICEs. All other demonstration projects started later than 1995.

Four demonstration projects include hydrogen ICE cars and vans, six (more recent) projects include fuel cell cars, three include hydrogen ICE buses, and nine include fuel cell buses.

Eight studies on hydrogen acceptance and social implications have been carried out so far, most of them in Germany. Three have been conducted in the course of a demonstration project. An international acceptance study has started recently. Locations included are London (UK), Berlin (Germany), Luxembourg (Luxembourg), Perth (Australia) and Oakland (California, USA). Passengers of hydrogen buses (fuel cells and ICEs) in demonstration projects will be surveyed.

Two central conclusions may be drawn from the existing studies: Hydrogen acceptance is generally high, and as soon as people experience hydrogen technology in their every-day life they accept and use it. This shows the importance of demonstration projects also in this respect.

Three reasons dominate people's appraisal of hydrogen vehicles: greatly reduced local emissions, noise reduction and a general perception of hydrogen as being a "clean energy".

In this chapter, available prototypes of transport systems using hydrogen including their technical and economic characteristics are being reviewed. For field trials results are collected and evaluated.

If not specified otherwise, the results presented represent LBST analyses.

3.1 Available prototypes

3.1.1 Road vehicles

Since 1967 some 110 different fuel cell vehicle prototypes have been developed, and some 36 different hydrogen internal combustion engine (ICE) prototypes [h2cars 2003]. Several of them have been built in more than one unit, summing up to a total number of some 230 fuel cell vehicles and some 66 ICE vehicles until the first months of 2003 (see Figure 3-1). Most of the vehicles have been presented after 1995.

None of these prototype vehicles is economically competitive with conventionally fueled ICE vehicles. Both propulsion source as well as hydrogen storage technologies are more costly than for conventional vehicles. The advantage of ICE vehicles is that they are presently much cheaper to manufacture than fuel cell vehicles as the ICE only has to be modified to hydrogen operation whereas FCVs require completely new manufacturing lines. FCVs at present are only hand-assembled and therefore extremely expensive. The same counts for advanced hydrogen storage vessels which will have considerably reduced costs in future mass manufacturing.

Each prototype fuel cell vehicle has costs of 1 to 10 million including research and development efforts, hand-crafted manufacture etc. These cost figures are not meaningful for future costs of mass manufactured series vehicles.

Figure 3-1: Presentation of fuel cell vehicles and of hydrogen ICE vehicles over the last three decades; status: March 2003 [h2cars 2003].

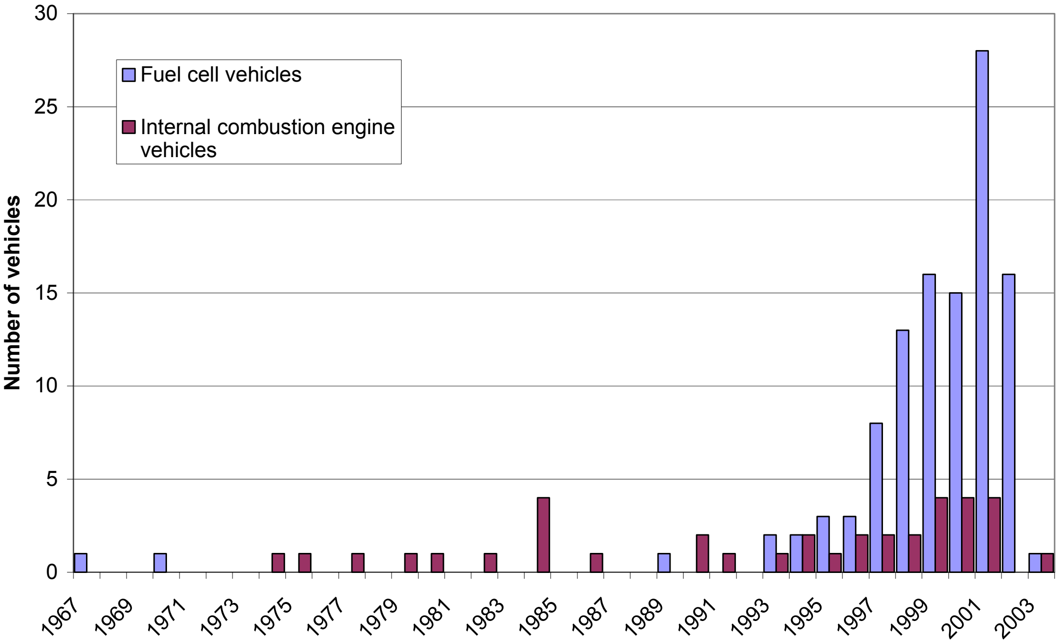


Figure 3-2 shows the evolution of fuel cell vehicle development from the first Mercedes-Benz NECAR 1 vehicle (‘a van for the transportation of fuel cells and hydrogen storage’), over the GM/Opel HydroGen 3, a fully useful five seat minivan, to a concept vehicle, the Toyota Fine-S, incorporating purpose design elements and presenting the concept of a later commercial sedan.

Presently, development criteria for fuel cell vehicles demand an operating range of 500 km as minimum requirement by the customer. The monofuel 20 MPa CNG vehicle Fiat Multipla Bluepower offers an operating range of 540 km. This vehicle designed as a fuel cell vehicle with 70 MPa CGH_2 storage (containing 55% of the energy compared to 20 MPa CNG and approximately double the fuel efficiency) would achieve a satisfactory operating range of 600 km. This demonstrates that purpose design cars can easily achieve satisfactory operating ranges with hydrogen storage concepts available in first commercial units.

Today, FCV prototypes still have about 25-30% higher curb weights than their conventional gasoline or diesel counterparts. This weight difference can be reduced over the years to come by continuous improvements in the hydrogen storage, fuel cell and drive train development to achieve weight penalties comparable to those of CNG vehicles. Their additional weight in comparison to the diesel or gasoline counterparts lies in the order of 10 – 15%, a value obviously accepted by the customer.

Figure 3-2: Fuel Cell Vehicle design evolution 1994 – 2003.

Over the last years significant progress has been achieved in the packaging of hydrogen storage equipment and of propulsion units, especially in the case of fuel cells. Fuel cells have increased their volumetric power densities by more than a factor of ten over the last decade. Engine capacities of up to 150 kW can be accommodated in the same engine compartment as comparably powerful ICEs (e.g. Opel HydroGen3). Still, all present prototypes being built in small numbers (e.g. DC F-Cell, Toyota, Honda, Opel HydroGen3) are 'conversion design' vehicles. The first 'purpose design' vehicles taking into account the special requirements derived from the fuel cell and hydrogen technologies are the GM Hy-Wire and Toyota Fine-S concept cars. Purpose design vehicles will come into realization when large numbers of FCVs are manufactured, representing high shares of the total manufacturing volume, in order to justify the development and production of a new platform modified to fuel cells and hydrogen storage. Similarly, Toyota is presently extending gasoline hybrid propulsion power trains over its entire product range in order to justify a purpose design vehicle platform for hybrid power trains.

3.1.2 Other transport modes

3.1.2.1 Submarines

A joint venture between the two German ship manufacturers Howaldtswerke-Deutsche Werft (HDW) and Nordseewerke Emden has entered a new stage of the fuel cell submarine test program. For the first time in spring 2003, the new hydrogen powered fuel cell submarine left the ship yard and the harbor in Kiel to be tested in the German Baltic Sea.

The PEM fuel cell engine has various advantages compared to a conventional diesel engine. It is more efficient and therefore the boat is able to stay under water for a longer time (up to 3 weeks). Siemens has developed and is manufacturing two different types of PEM fuel cell modules, one type for the German and Italian U212 submarines and the other one for the U214 submarine, which will be used by the Greek and the South Korean navy.

Furthermore, the new propulsion system does neither emit any heat nor any detectable noise which makes it rather difficult to locate. For military applications, this has great tactical benefits.

The hydrogen refueling station for the submarine is built around Air Products' cryogenic hydrogen gas and liquid compressor technology and has been designed to minimize refueling time.

The German Navy plans to deploy four of these submarines from 2004 on.

3.1.2.2 H_2 boats and ships

In Germany, Hydra, a passenger boat with a 7.5 kW alkaline fuel cell propulsion unit and room for 22 passengers, was launched in the summer of 2000. The boat was tested successfully on various rivers and lakes in Germany. At present, there are no commercialization activities.

Already in the late 1990ies a passenger boat was converted to PEMFC propulsion in Italy, which was never operated in public service.

On February 20, 2003, the Water Transit Authority (WTA) of San Francisco, USA, a regional transit agency, announced that it was awarded US-$2.5 million in federal funds to build the world’s first fuel cell powered commuter ferry, a 49-passenger boat. The WTA expects the boat could be ready to sail by as early as 2006, if other funding and necessary approvals are secured.

In Iceland there is a strong interest in converting the fishing fleet to hydrogen power. In spite of large untapped resources of cheap renewable power, Iceland has to import significant quantities of oil to power fishing vessels and road transport. Introducing hydrogen in these applications could relieve the national budget and reduce GHG emissions significantly. Norsk Hydro, Shell and DaimlerChrysler are expected to get involved in this project through the company Icelandic New Energy.

There are also several other studies on the use of fuel cells in ships and submarines mostly with a defense background. The EU-funded project FCSHIP looks at fuel cells for civil marine applications.

3.1.2.3 Hydrogen aircraft

In September 2002, Boeing Co. received a small Pentagon contract (300,000 $) to design a fuel cell-based propulsion system for a new pilotless aerial vehicle (UAV) that could eventually stay in the air at high altitudes for weeks rather than days [Boeing 2002]. The new long-endurance UAV could play a vital role in future communications and military systems. During the first phase of the project, Boeing will lead a team to design the UAV's fuel cell-based propulsion system, drawing on currently available automotive fuel cell technology, and conduct risk-reduction studies. In a second phase, planned for 2003, Boeing will build and demonstrate the complete propulsion system, with the actual aircraft to be built in a third phase.

NASA’s Helios research plane which has a wingspan of about 82 m, powered by 14 tiny propeller motors is designed to reach high altitudes and stay aloft for up to three months. It is intended to function like a “poor man's satellite”, providing telecommunications and other services at a fraction of the cost of launching a satellite into orbit. Traveling close to the Earth, rather than in space orbit like a satellite, it can be brought down easily for routine maintenance and payload changes.

Engineers have developed a lightweight fuel cell system that allows the craft to fly at night by storing the excess solar power it generates. For the first flight tests the Helios had batteries that allowed it to stay up for just a few hours after sunset. The solar cells generate about 40 kW of electric power for the propeller motors. Fuel cells were installed in summer 2003. During the first test flight, Helios was destroyed when it crashed during a checkout flight from the Hawaiian island of Kauai. The exact cause of the crash is still unknown, but an interim status report released by the Mishap Investigation Board July 8 indicates the Helios prototype appeared to have experienced undamped pitch oscillations that led to a partial breakup of the aircraft in mid-air while flying at about 3,000 feet altitude [Helios 2003].

AeroVironment, Inc. developing the fuel cell system is pursuing commercial applications for the craft, whereas the government plans to use the Helios for a variety of earth science research programs, such as remote-sensing and imaging of the earth's atmosphere and water to study global warming and ozone depletion. Further uses may be monitoring the health of fisheries and forest resources, tracking of natural events like hurricanes, tornadoes and volcanic eruptions and even determine the readiness of agricultural crops for harvest. The military also may use the Helios for surveillance activities because it is essentially a stealth aircraft that is silent and cannot be detected by radar. At maximum altitude, it can fly at speeds of about 200 miles (320 km) per hour.

On 06 May 2003, NASA has reported that researchers at the Glenn Research Center are exploring the possibilities of developing a fuel-cell powered jetliner [Boeing 2003]. The project, part of NASA’s Revolutionary Aeropropulsion Concepts program, is looking at developing a passenger aircraft of the scale of a Boeing 737, propelled by electric motors incorporating “superconducting aluminum” and fuel cell power. NASA thinks that fuel cells offer the greater long-term benefit if they can be made to work because they have a higher inherent thermal efficiency than conventional aircraft engines. Conventional wisdom is that PEMFC propulsion systems including electric motors would have to increase in power density (kW per kg) by factors of five in order to be suitable even for small airplanes, with additional increases in power density required for large aircraft.

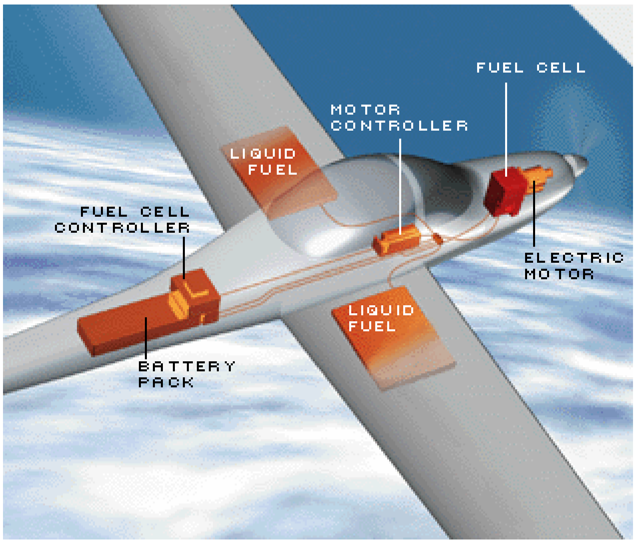
NASA is also involved in a small, two-seat plane using PEM fuel cell power being developed by FASTec, a non-profit foundation. This activity continues since April 2002, when Boeing started designing a small fuel-cell-powered propeller plane. Boeing hopes to get its test plane off the ground by 2004 (see Figure 3-3).

In July 2003, Boeing has announced its partners for a demonstrator airplane project aimed at exploring the use of fuel cell technology for future aerospace applications. The research project, led by the Boeing Research and Technology Center in Madrid, Spain, includes Intelligent Energy (UK), Diamond Aircraft Industries (Austria), the Spanish companies Sener and Aerlyper, and Advanced Technology Products (ATP), from the United States. In addition, Polytechnic University of Madrid and Polytechnic University of Catalonia will be involved in the project. Work to integrate the fuel cells into the demonstrator airframe is expected to begin at the end of summer 2003. This would enable a possible flight test in late 2004 or early 2005. While test results are not expected to allow for any near-term applications of the new technology to production aircraft, they are expected to contribute to the eventual use of this technology in aircraft to provide cleaner, more efficient performance [HyWeb 2003].

If its research bears fruit, there could be a place for fuel cells in jetliners, too, replacing the gas turbine auxiliary power units (APU) built into the rear fuselages of jets. Currently, the APU generates electrical power for the jet primarily when the main engines are switched off. But a fuel cell APU could be used in flight for everything from heating meals to powering the cockpit's computer – instead of diverting power from the main engines to generate electricity and heat – thus improving the plane's overall fuel efficiency. Similar ideas are being developed by Airbus in Europe [Masterflex 2003].

Operating fuel cells at high altitudes brings about new technical challenges as the air is very cold (down to -55°C) and has a low density.

Figure 3-3: Artist's view of Boeing's fuel cell powered propeller prototype plane.



3.1.2.4 Hydrogen tramway and train

At the beginning of 2003, the New York City Transit Authority has agreed to allow a technical consortium of US-American companies to develop and demonstrate the world's first fuel cell powered locomotive for a municipal subway system. The overall, three-phase project will develop and demonstrate a 50-ton, 250 kW fuel cell powered utility locomotive that pulls flatcars carrying track materials and equipment into subway tunnels [ABBA 2003].

The project has been prepared over the past two years and recently a small 4 ton locomotive powered by a 14 kW fuel cell has been produced, tested and accepted for the gold mining industry [fcp 2003]. It was proven that the technology will work reliably and safely underground. After a six month engineering study, the fuel cell will be manufactured, installed and tested in railroad operations. The project is scheduled to be completed by 2005.

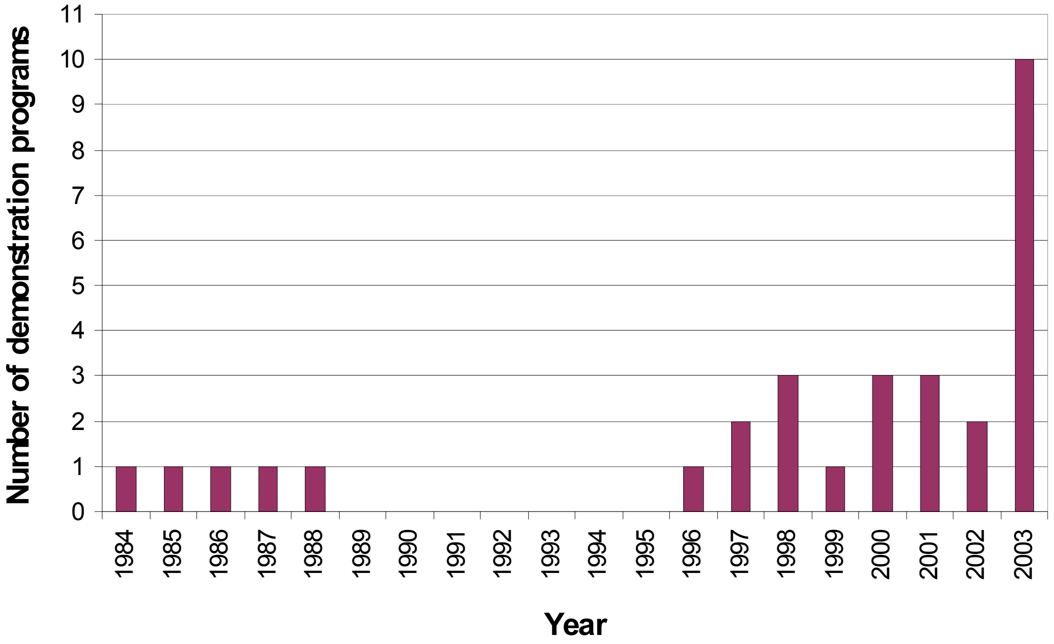
Several design studies have been made and projects been developed for hydrogen fuel cell powered regional trains and tramways in Europe. Nonetheless, no concrete development efforts are made at present.

3.2 Field trials

The development pace of hydrogen technology has sharply accelerated during the last half decade. By nature, demonstration programs represent the last stage in the technology R&D and commercialization procedure and thus follow R&D efforts with a certain time delay. 20 fleet demonstration activities of hydrogen ICE or fuel cell vehicles have been carried out or are in concrete planning at present (see Figure 3-4). The first fleet demonstration project took place in Germany between 1984 and 1988 with 10 cars and delivery vans powered by hydrogen ICEs. All other demonstration projects started later than 1995.

Four demonstration projects include hydrogen ICE cars and vans, six (more recent) projects include fuel cell cars, three include hydrogen ICE buses, and nine include fuel cell buses.

Figure 3-4: Hydrogen road vehicle field trials over the past 20 years.



More recently, some large fuel cell projects have been started, such as the California Fuel Cell Partnership, the European CUTE and CITYCELL projects, the Japanese Hydrogen Fuel Cell Project (JHFC), the UNDP-GEF fuel cell bus demonstration, the GM-Shell project in Washington, D.C., USA, and the Clean Energy Partnership Berlin, the latter comprising fuel cell and hydrogen ICE vehicles. First fleets of fuel cell passenger cars are given to customers. Toyota and Honda have already delivered cars to clients on a leasing basis, DaimlerChrysler and General Motors/Opel will do so this year. Political, administrative and university bodies were the target group of the first tranche. The field trials shall prove the technological viability of hydrogen powered cars and infrastructure as well as raise acceptance of decision makers.

Recently started bus demonstration programs are ambitious. The number of participating vehicles is rather high considering the potential market volume, yet required to draw statistically valid conclusions. Their scope covers several European nations (CUTE, CITYCELL) or worldwide (UNDP-GEF). Their main project goals are very similar to those of car field trials with a strong focus on commercialization/mass production.

For methodological reasons, it is difficult to draw conclusions from terminated field trials regarding technical performance data as the numbers of vehicles per cohort are statistically not significant. Nonetheless, development has greatly benefited from the experiences gained in field trials. These results have fostered further product development in many aspects. Unfortunately, only very limited results have been published.

"Early" demonstration projects have included vehicles not suitable for commercial series production. Rather, they have helped companies to develop commercially viable vehicles, which are demonstrated in the upcoming projects such as CUTE and CITYCELL for buses or the JHFC for passenger cars. Goals of the "early" demonstration projects included the demonstration of principal viability, the "curing of teething troubles", making first experiences with customers (operators of city buses, bus passengers) etc.

Limited data are available on the mileage of hydrogen vehicles in demonstration projects. Mileage proven by hydrogen ICE vehicles is in general significantly higher than the mileage proven by fuel cell vehicles. Due to their lower system complexity, ICE-driven hydrogen vehicles showed a higher availability and performed more operating hours than fuel cell powered vehicles. No comparative analyses have been made public so far regarding air and noise emission reductions realized by H_2-ICE and fuel cell powered vehicles in real-life applications.

The upcoming demonstration projects in contrast are carried out with vehicles ready for series production. They have the goal to collect performance data of the vehicles such as fuel efficiency (depending on driving cycle and operation mode), technical availability, lifetime etc. Preliminary technological and economic results from the first phase of the latest field trials may be expected by the end of 2003 at the earliest. Most of these results will not be published.

The costs of demonstration programs are rather high due to the fact that both the vehicles and the corresponding hydrogen refueling infrastructure have to be provided.

Eight studies on hydrogen acceptance and social implications have been carried out so far. Germany has been the geographical scope of six of these studies, one has been carried out in the United Kingdom, an international study is ongoing. Three out of seven concluded studies have been conducted in the course of a demonstration project.

An international study (AcceptH_2) funded by the European Commission for the European part has started recently. Locations included are London (UK), Berlin (Germany), Luxembourg (Luxembourg), Perth (Australia) and Oakland (California, USA). Passengers of hydrogen buses (fuel cells and ICEs) in demonstration projects will be surveyed [AcceptH2 2003].

Two central conclusions may be drawn from the existing studies: Firstly, hydrogen acceptance is generally high and does not appear to be a major obstacle to commercialization, yet it should be a regular issue in project planning. Secondly, as soon as people experience hydrogen technology in their every-day life they accept and use it. This shows the importance of demonstration projects also in this respect.

Three reasons dominate people's appraisal of hydrogen vehicles: greatly reduced local emissions, noise reduction and a general perception of hydrogen as being a "clean energy".

Field trials will keep on playing a vital role in the course of hydrogen technology commercialization by shortening the learning curve and creating public awareness of the new technology.

3.3 Literature

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4 TECHNICAL, REGULATORY, ECONOMIC, MARKET AND OTHER OBSTACLES AND POTENTIAL INSTRUMENTS TO OVERCOME THEM

Several obstacles have to be overcome for the large scale market introduction of hydrogen as transport fuel. At the same time, there are a number of driving forces.

Obstacles are identified and assessed, and potential instruments to overcome them are listed.

Pre-eminent obstacles are identified in the field of technology, regulations, economics and markets: Both fuel cell and hydrogen storage technologies require further advances of performance parameters in order to compete with conventional technology. The technologies must be suitable for mass manufacturing, and the manufacturing costs in mass production must be competitive to conventional power trains. Regulations, codes and standards in all areas of hydrogen fuel must be developed and harmonized, mostly on international level. A hydrogen infrastructure has to be built up.

There is growing evidence that all obstacles can be overcome. A common strategy of industry, politics and research for a fast market uptake is key to meeting these challenges.

Pre-eminent drivers come from different societal directions. Hydrogen fuel has the potential for significant environmental and health improvements, especially climate protection and increased local air quality. Hydrogen allows for a diversification of primary energy sources increasing the security of energy supply. Fuel cells are a basic technology innovation allowing for new and advanced products and services. The modularity of fuel cell technology promises synergies between mobile, stationary and portable applications, and allows for a much easier up and down-scaling of the technology to higher or lower power levels significantly reducing development efforts.

Promising pathways exist to achieve the goals of climate protection, supply security and increased economic competitiveness at the same time. Hydrogen and fuel cells seem to open the best chances and largest market potentials of all alternatives in the transport sector.

More obstacles and drivers of secondary importance are compiled and discussed.

The following tables summarize the obstacles and drivers including an assessment when solutions for the obstacles are required and when first positive effects may be expected for each of the drivers.

Table 4-1: Overview of obstacles

Pre-eminent obstacles		Solutions required
Technical	Fuel cell technology	S
	Hydrogen storage technology, including mass manufacturing	S/M
Regulatory	Regulations, codes and standards in all areas of hydrogen fuel	S
Economic	Fuel cell vehicle costs	S/M
Market	Hydrogen infrastructure	S/M
Major obstacles		
Technical	Mass manufacturing of fuel cells	S/M
	Mass manufacturing of hydrogen components	S/M
Economic	Fuel cell vehicle costs	S/M
	Hydrogen fuel costs	S/M
Market	Consumer awareness	M
Other	Appropriate political framework	S/M
	Fragmented, incoherent approach (funding, regulations etc.) in Europe	S
	Information and education	S+M+L
Minor obstacles		
Technical	Infrastructure components	S
	Hydrogen production from biomass	S/M
	Vehicle integration	S
Market	Fragmentation of alternative fuels scene	S/M
	Insufficient availability of renewable energies	M/L
	Focus on wrong ‘early target markets’	S
Other	Debate of ecological advantages	S+M+L
Undefined obstacles		
Market	Public acceptance	S/M

Table 4-2: Overview of drivers

Pre-eminent drivers		First positive effects expected
	Environmental integrity and health improvements	M/L
	Energy security and supply	M/L
	Fuel cells are a basic technology innovation promising major advantages	M/L
Major drivers		
	Economic competitiveness	M
	Reconciliation of major goals	L
	Positive company image	S
	Increased energy efficiency	M/L
	Smooth transition from fossil to renewable	M/L
	Maximum feedstock flexibility	M/L
Minor drivers		
	Additional market for renewable energies	M/L
	"All electric car"	M

S – short-term (until 2010)
M – mid-term (2010-2020)
L – long-term (2020-2030)
VL – very long-term (beyond 2030)

In this chapter, the technical, regulatory, economic, market and other obstacles of the large-scale introduction of hydrogen as transport fuel will be identified, and potential instruments to overcome them will be proposed. Many of the technical obstacles are effectively of techno-economic nature requiring technical solutions that allow to achieve cost goals by reducing material costs and by allowing for mass manufacturing.

In addition, the main drivers towards hydrogen use in transportation will be made explicit in order to allow for a balanced view of obstacles and drivers.

There are several similarities between hydrogen and natural gas fuel, but also some important differences. Both fuels are gaseous building on similar technologies (compression, metering, dispensing etc.) and having similar safety features. Similar to natural gas, hydrogen fuel competes against well-established conventional fuels (gasoline, diesel).

In contrast to natural gas, a gradual introduction of hydrogen fuel is difficult in connection with fuel cell cars because natural gas vehicles are mostly bi-fuel and therefore do not depend on a filling station infrastructure with full area coverage. While hydrogen internal combustion engine vehicles can be bi-fuel as well, fuel cell vehicles are mono-fuel vehicles requiring a full area coverage of hydrogen filling stations. Another important difference between natural gas and hydrogen is that conventional gasoline cars can be retrofitted becoming bi-fuel cars. Fuel cell cars will always be original equipment manufacturer (OEM) vehicles, and the retrofit of gasoline cars to hydrogen engine cars is difficult resulting in reduced efficiency and possibly higher emissions than OEM cars.

The obstacles and drivers and the potential instruments to overcome them compiled in this chapter are based on results from several working groups/ projects and publications, especially the High Level Group on Hydrogen and Fuel Cells [HLG 2003] and HyNet [HyNet 2003]. This presentation cannot claim to be exhaustive, but it should contain the most important obstacles and drivers.

The rating assigned to the obstacles and drivers is an assessment by the authors.

4.1 Technical Obstacles

4.1.1 Fuel cell technology

A satisfactory balance between technical properties, durability and cost has not yet been achieved for PEM fuel cells. Four requirements have to be met in one PEM stack technology: mass manufacturability, low platinum load, high power density, sufficient lifetime. This requires among others improvements of bipolar plates (metal, composite materials), development of new membranes without the need for humidification, mid-temperature membranes, new catalyst developments (other materials, other processes and concepts for platinum etc.).

On system level, improvement of the system reliability, increase of system life time, reduction of system complexity etc. are requirements.

Rating

Pre-eminent obstacle

Potential instruments to overcome this obstacle

- Support for the commercialization and industrialization of research and development results.
- Continued support of basic research on materials and concepts of fuel cell component and stack technology.
- Improved support for small and medium-size enterprises active in this field including reduction of administrative barriers for funding.

4.1.2 Hydrogen storage technology, including mass manufacturing

Advanced conventional hydrogen storage concepts (70 MPa CGH_2, LH_2) compromises vehicle design or interior space availability and poses safety questions. Further advances in hydrogen storage are highly desirable reducing these constraints.

In addition, conventional storage technologies require further development in order to allow for mass manufacturing; first mass manufacturable systems are expected to be available by 2006-2008.

Rating

Pre-eminent obstacle

Potential instruments to overcome this obstacle

- Establishment of a research and funding focus for hydrogen storage technologies.
- Support for the development of mass manufacturable advanced conventional hydrogen storage technologies.

4.1.3 Mass manufacturing of fuel cells

Processes for mass manufacturing of fuel cells (components, stacks, BOP components) have to be developed as cost goals in automotive applications can only be met in mass production comparable to the manufacturing of conventional drive trains (several 100,000 units in one assembly line).

Rating

Major obstacle

Potential instruments to overcome this obstacle

- Support of R&D of manufacturing technologies.
- Strategic industrial and political orientation towards a fast market uptake of fuel cells.

4.1.4 Mass manufacturing of hydrogen components

Hydrogen components are manufactured in single or very low number series at present. This includes hydrogen and safety components onboard vehicles (storage vessels, valves, piping elements, pressure relief devices, sensors etc.), which would be required in 100s of thousands of units per year, and components and equipment for refueling infrastructure (electrolysers, reformers, compressors, piping elements, meters, dispensers, sensors etc.), required in 100s to 1000s per year.

Rating

Major obstacle

Potential instruments to overcome this obstacle

- Consensus for an integrated hydrogen introduction strategy (road map) on European level (see 4.5.1) between politics, industry and society giving industry a reliable policy framework required for the development of manufacturing technologies and building up manufacturing facilities.
- Support for the development of mass manufacturable components and manufacturing technologies.

4.1.5 Hydrogen production from biomass

Hydrogen production from biomass promises lowest renewable hydrogen production costs and is therefore desirable as an early cheap source of clean hydrogen. Development activities on the other hand are very limited. Prototype testing and design improvements have to be finalized until 2005-2007 in order to have the technology available commercially by 2010 for the market introduction of fuel cell cars (see 4.4.1).

Rating

Major obstacle

Potential instruments to overcome this obstacle

- Focus of RD&D funding on hydrogen from biomass.

4.1.6 Infrastructure components

Infrastructure components such as compressors, onsite storage, compact reformer technology, purification equipment, high pressure valves, fittings and safety equipment for the 70 MPa onboard pressure level (84.5 MPa dispensing pressure level) require development and continued improvement. Development aspects are performance, reliability, integrability into refueling stations, costs etc. Problems are on the way to be solved technically, no breakthroughs are required. Improved designs still need some time and funding. Most development work in this area is carried out by small and medium-sized enterprises.

Rating

Minor obstacle

4.1.7 Vehicle integration

Vehicle integration of hydrogen storage requires optimized system integration and adapted vehicle designs in order to allow for enhanced operating ranges while maintaining maximum interior space and comfort (see 4.1.2). No technical breakthroughs are required.

Rating

Minor obstacle

4.2 Regulatory obstacles

Regulations (legal requirements, codes of practice, etc), standards and legislation in general are an area of utmost importance for the commercialization of hydrogen fuel. Without the development of proper regulations and standards, commercialization will not be possible. The major areas concerned are hydrogen onsite production and storage, refueling interfaces and vehicle approval.

An important activity is the European Integrated Hydrogen Project [EIHP 2003] working on regulations for the approval of hydrogen road vehicles to be adopted by UNECE by 2005/06, and on defining requirements for standards organizations with respect to refueling infrastructure and refueling interface.

ISO (International Organization for Standardization) working on standards for stationary hydrogen applications and for hydrogen components for onboard vehicle use and for stationary use, and IEC (International Electrotechnical Commission) working on standards for fuel cells in mobile or stationary use are the major international activities on the harmonization of standards.

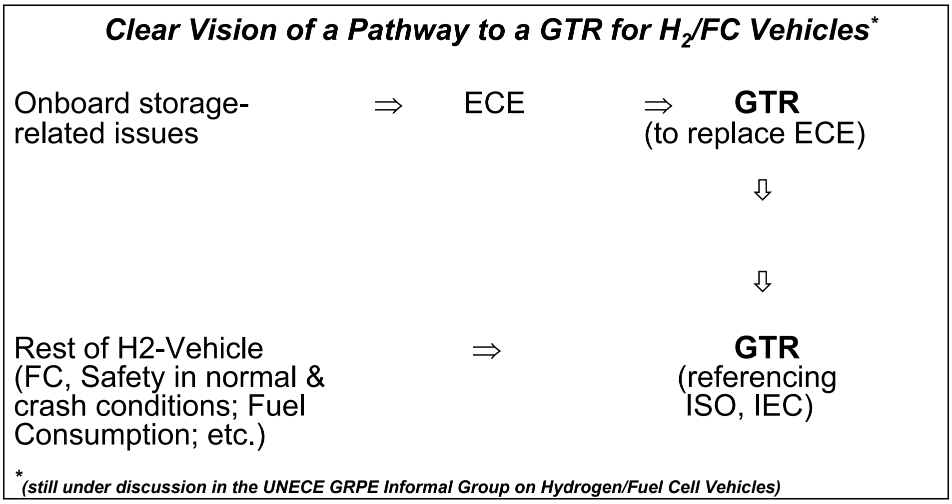
Internationally harmonized regulations are required for hydrogen vehicle approval. In Europe at present, the UNECE regulations and the EEC directives are the legal framework for vehicle approval. Both cover different parts and items of a vehicle. For Europe a Whole Vehicle Type Approval (WVTA) is feasible only via EEC directives. Due to mutual recognition of UNECE by the EEC (European Economic Community) directive mechanism, the Whole Vehicle Type Approval (WVTA) by EEC is ensured.

As for the hydrogen onboard storage and supply part of the vehicle neither ECE regulations nor EEC directives did exist, since 1999 EIHP undertook the exercise to draft such regulation documents for submission to UNECE. Other ECE regulations and EEC directives rule other safety relevant parts of the vehicle. These regulations had to be adapted to hydrogen technology as well. EIHP also in this area undertook the efforts to develop and submit amendments to these regulations, in particular the following ones:

Subject	EEC-Directive/ECE-Regulation
1. Emissions	70/220/EEC incl. latest amendment & ECE R83
2. Fuel tanks/rear protective device	70/221/EEC incl. latest amendment & ECE R34/58
3. Diesel smoke	72/306/EEC incl. latest amendment & ECE R24
4. Identification of controls	78/316/EEC incl. latest amendment
5. Fuel consumption	80/1268/EEC incl. latest amendment & ECE R 101
6. Engine Power	80/1269/EEC incl. latest amendment & ECE R84
7. Diesel emissions	88/77/EEC & ECE R49
8. Side impact	96/27/EC & ECE R95
9. Frontal impact	96/79/EC & ECE R94
10. Roadworthiness tests	96/96/EC & PTI
11. CO2 labeling	99/94/EC
12. Base Directive	70/156/EEC incl. latest amendment
13. Electric Vehicles	NEW EC Directive & ECE R100
14. Defrost/Demist	78/317/EWG (already under progress)

Finally, by all internationally active automotive manufacturers a Global Technical Regulation (GTR) is aimed at. The globalization of the approval of hydrogen fueled road vehicles shall be achieved by developing Global Technical Regulations (GTRs). The GTRs will be submitted to WP.29 of UNECE for discussion and approval. As soon as the GTRs are approved, they will replace the UNECE regulation for Europe.

For a GTR all hydrogen derived safety relevant aspects have to be merged as far as possible into one GTR. This process is depicted in the following graph, taking into account the onboard storage aspect (as to be ruled in a UNECE regulation) and the other hydrogen-related safety relevant issues (as e.g. fuel cell, safety in normal and crash condition, fuel consumption etc.).



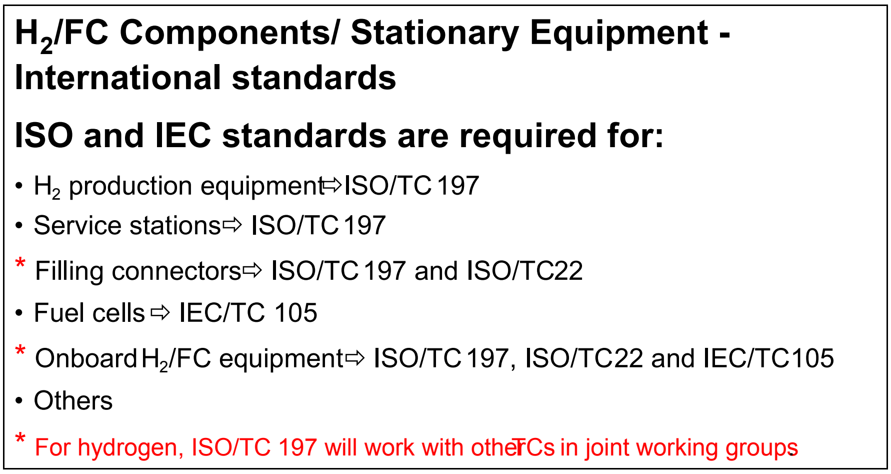
Clear Vision of a Pathway to a GTR for H_2/FC Vehicles*

****(still under discussion in the UNECE GRPE Informal Group on Hydrogen/Fuel Cell Vehicles)***

The best estimate to have such a GTR in place for hydrogen fuelled road vehicle is 2010.

Hydrogen components for the onboard use in vehicles, as well as for the off-board interconnection with the vehicle (refueling interface) as well as for stationary applications (e.g. refueling station, onsite hydrogen production units, hydrogen storage, hydrogen using appliances) are (to be) standardized internationally by ISO (International Organization for Standardization). Fuel cell specific issues for mobile and stationary use are (to be) standardized internationally in IEC (International Electrotechnical Committee).

Examples are depicted in the following graph:



H_2/FC Components/ Stationary Equipment - International standards

ISO and IEC standards are required for:

- H_2 production equipment ⇨ ISO/TC 197
- Service stations ⇨ ISO/TC 197
- * Filling connectors ⇨ ISO/TC 197 and ISO/TC22
- Fuel cells ⇨ IEC/TC 105
- * Onboard H_2/FC equipment ⇨ ISO/TC 197, ISO/TC22 and IEC/TC105
- Others

* For hydrogen, ISO/TC 197 will work with other TCs in joint working groups

National or European legislation is required for hydrogen filling stations and onsite hydrogen production.

4.2.1 General Observations on Standards for Stationary H_2 Generation, Handling and Use

Standards are

- no legal requirements (possibly will become legal requirements if cross-referenced in national legislation),
- made by interested parties,
- supposed to give recommendations about safe solutions and practice on the particular topic/ installation/ equipment,
- supposed to support the free exchange of goods and services.

Examples of standards organizations are:

- ISO (International Organization for Standardization)
- IEC (International Electrotechnical Commission)
- NFPA (National Fire Protection Agency)
- ASME (American Society of Mechanical Engineers)
- ANSI (American Society of Mechnical Engineers)
- SAE (Society of Automotive Engineers)
- International Code Council (ICC) H2 Ad hoc Committee

- CGA (Canadian Gas Association)
- CSA (Canadian Standards Association)

4.2.2 General Observations on EU Directives and International Regulations

Legal Requirements and Regulations are ranked above standards.

EU directives express the frame requirements for national regulations in the different European member countries.

Important directives regarding hydrogen technologies and infrastructure are:

European directives

- EEC directives (as e.g. Council Directive 70/156/EEC of 6 February 1970 on the approximation of the laws of the Member States relating to the Type-Approval of motor vehicles and their trailers)
- ATEX directives
- PED (Pressurised Equipment Directive)
- EMC (electromagnetic compatibility) directive
- The Machinery Safety Directive
- SEVESO II (large amounts of hazardous material)
- Transport of dangerous goods by road (Council Directive 94/55/EC amended by Commission Directive 2003/28/EC of 7 April 2003 and 2001/505/EC: Council Decision of 26 June 2001 on the accession of the European Community to United Nations Economic Commission for Europe Regulation No 105).

International regulations

- UNECE regulations (e.g. according to 1958 agreement [E/ECE/324-E/ECE/TRANS/505/Rev.2]),
- GTR according to the 1998 agreement [E/ECE/TRANS/132 AND Corr.1],
- UN IMO (International Maritime Organization).

Rating

Pre-eminent obstacle

Potential instruments to overcome this obstacle

- A strategic initiative to develop, harmonize and improve regulations, codes and standards for hydrogen and fuel cells following the example of Japan developing and deregulating codes, standards and test procedures for all hydrogen and fuel cell related issues until 2005. This strategic initiative should not rely on short term funding from the framework programs, but should be funded in a mid-term perspective on a continuous basis (see EIHP – European Integrated Hydrogen Project as an example [EIHP 2003]).

4.3 Economic Obstacles

4.3.1 Fuel cell vehicle costs

The costs of fuel cell vehicles, which are presently driven by the costs of the fuel cell powertrain and the hydrogen storage, have to be reduced to levels comparable to conventional vehicles.

The automotive industry expects to achieve these cost goals at production volumes of several 100,000 units per year in one assembly line, which is the common capacity for conventional vehicles.

Rating

Major obstacle

Potential instruments to overcome this obstacle

- Appropriate fuel cell technology (see 4.1.1) and mass manufacturing (see 4.1.3).
- Advanced hydrogen storage technologies and mass manufacturing (see 4.1.2, 4.1.3).

4.3.2 Hydrogen fuel costs

Detailed analyses have shown that hydrogen fuel costs can come down to commercially viable levels if significant shares of the fuel market can be tapped. Cost per kilometer driven is the decisive comparative cost figure, allowing hydrogen to be up to twice as costly as conventional fuels because of the higher efficiency of fuel cell powertrains.

Also hydrogen from certain renewable sources of energy can become cost competitive in the mid to long-term.

Rating

Major obstacle

Potential instruments to overcome this obstacle

- Long-term warranty on economic incentives, in particular fuel tax reductions, ensuring consumer confidence and planning security for industry.
- Public support for the build-up of a hydrogen refueling infrastructure (see 4.4.1).
- Continued market introduction support for renewable energies.

4.4 Market Obstacles

4.4.1 Hydrogen infrastructure

Hydrogen road vehicle infrastructure development and deployment in a timely manner is a prerequisite to the commercial introduction of hydrogen vehicles. For the general market introduction of hydrogen (fuel cell) cars expected around 2010 a hydrogen refueling infrastructure with full area coverage in starter market countries is required. This implies an initial investment which will be recovered after a number of years due to a low utilization rate during the first years of hydrogen car commercialization.

Rating

Pre-eminent obstacle

Potential instruments to overcome this obstacle

- Good coordination of infrastructure development and hydrogen vehicle manufacturing capacities (see 4.5.1).
- Tax incentives, subsidies, other financial incentives for hydrogen refueling infrastructure; public-private partnership.
- Legal requirement for car fuel retailers to equip a certain share (e.g. 20%) of their refueling sites with hydrogen facilities.

4.4.2 Consumer awareness

Consumer awareness of hydrogen vehicles is generally low as so far no vehicles are offered commercially (see 4.5.3). In some key countries (Germany, USA, Japan) the awareness of the general public has been attracted during recent years by public relations activities of car manufacturers presenting hydrogen and fuel cell prototype vehicles.

Rating

Major obstacle

Potential instruments to overcome this obstacle

- Awareness campaigns to increase market acceptance for hydrogen vehicles.
- Supported introduction of hydrogen vehicles in public transport and other fleets with high public visibility.

4.4.3 Public acceptance

Public acceptance refers to perceptions and valuations of the general public concerning hydrogen, referring to safety, environmental aspects, consumer relevant parameters etc.

First studies undertaken at national and international level indicate that this might be no problem as acceptance levels are generally high in spite of the fact that knowledge is generally low (see 4.5.3). A major accident in the early phase of commercialization may represent a major setback or could reverse the situation entirely.

Rating

undefined

Potential instruments to overcome this obstacle

- Additional consumer acceptance assessments.
- Demonstration activities with high outreach and public visibility.

4.4.4 Fragmentation of alternative fuels scene

Funding and commercial efforts are split between several alternative fuels such as biofuels (fatty acid methyl ester [FAME], ethanol, synfuels, MTBE, ETBE), natural gas (CNG), propane/butane (LPG) and hydrogen.

Rating

Minor obstacle

Potential instruments to overcome this obstacle

- Alternative fuels strategy on European level. First steps are the alternative fuels directive proposing goals for market shares of alternative fuels [EU 2003] and the White Paper on EU Transport Policy [EU 2001]. Such a strategy should clearly indicate the different time horizons and the different potential market sizes especially with respect to biofuels.

4.4.5 Insufficient availability of renewable energies

Major environmental motivation for the establishment of a hydrogen economy are the potential advantages, especially a reduction in local pollutant emissions and greenhouse gas emissions. The latter requires abundantly available renewable energies for the production of hydrogen fuel.

Rating

Minor obstacle

Possible instruments to overcome this obstacle

- Support and strategies on national and EU levels for the accelerated market establishment of renewable energies.

4.4.6 Focus on wrong ‘early target markets’

Insufficient understanding of obstacles and drivers as well as of market structures and dynamics has led to a rather broad misconception that public transport and other captive fleets would represent an early starter market avoiding the infrastructure problem and allowing for an equal growth of infrastructure and vehicle population (see 4.4.1). This does not take into account the requirement for mass manufacturing in order to come close to the cost goals of fuel cell propulsion.

Rating

Minor obstacle

Possible instruments to overcome this obstacle

- An integrated European hydrogen introduction strategy (see 4.5.1, 4.5.2).

4.5 Other Obstacles

4.5.1 Appropriate political framework

Compared to Japan and the USA, the European Union and its member states are lacking comparable support for hydrogen and fuel cells. In addition to the insufficient level of funding the continuity of funding is compromised by long project lead-times and discontinuous funding through irregular calls for proposals.

Increased and continuous funding is a major requirement for RD&D and the early commercialization phase (see also 4.3.2, 4.4.1).

Rating

Major obstacle

Possible instruments to overcome this obstacle

- A dedicated budget for hydrogen and fuel cells (see also chapter 8.1.3).
- Increased funding for hydrogen and fuel cells (see also Chapter 8.1.4).

4.5.2 Fragmented, incoherent approach (funding, regulations etc.) in Europe

Strategies on regional, national and European level for hydrogen and fuel cells are very diversified making it practically impossible to get an overview. Industry and research are given very diverse starting conditions for their developments in Europe.

Rating

Major obstacle (see 4.2, 4.4.4, 4.5.1)

Possible instruments to overcome this obstacle

- An integrated European strategy on hydrogen as proposed by the European Commission on September 10, 2003, through the establishment of a European Hydrogen and Fuel Cells Technology Partnership devising a Hydrogen Research Strategic Agenda. This shall include the establishment of a policy framework that is coherent across transport, energy and environment to reward technologies that meet policy objectives.
- Consensus for an integrated hydrogen introduction strategy (road map) with binding obligations and milestones on a European level (see 4.5.1) between politics, industry and society giving industry a reliable policy framework.
- A strategic initiative to develop, harmonize and improve regulations, codes and standards for hydrogen and fuel cells (see 4.2) in cooperation with major world regions such as USA, Japan and China.

4.5.3 Information and education

Knowledge about hydrogen and fuel cells is generally very low (see also 4.4.2, 4.4.3), both in the general public and among professionals who are potentially concerned. Hydrogen and fuel cells are in general not covered by school or university curricula. This obstacle has both a short-term and a long-term relevance.

Rating

Major obstacle

Possible instruments to overcome this obstacle

- A Europe-wide education and training programme, from schools to world-class research as proposed by the European Commission on September 10, 2003 [EC 2003].
- A communication and dissemination centre for all initiatives proposed by the European Commission on September 10, 2003 [EC 2003].
- Long-term strategy for public education and outreach on EU level accompanying research, development and demonstration from the earliest stages. Given the current disproportion between RD&D and public education and outreach activities, there is an urgent need for such a strategy on the side of the European Commission, and for significant budgets allocated to public education and outreach.

4.5.4 Debate of ecological advantages

There is a debate among ecologically oriented organizations whether hydrogen fuel is or can be a sustainable vehicle fuel. On the one hand, there is some skepticism whether hydrogen would actually be produced from renewable energies in the mid-term or whether hydrogen would be mainly produced from coal and from nuclear power. On the other hand, it is argued that renewable electricity should be used in stationary applications first because the CO_2 emission savings are higher there than in hydrogen fuel production and use in road vehicles.

Rating

Minor obstacle

Possible instruments to overcome this obstacle

- A convincing political communication embedding hydrogen in a sustainable energy and transport scenario.
- An open scientific and political debate.
- Inclusion of industry-independent non-governmental organizations in the European Hydrogen and Fuel Cells Technology Partnership devising a Hydrogen Research Strategic Agenda proposed by the European Commission on September 10, 2003.
- Labeling of hydrogen at public filling stations displaying the Well-to-Tank greenhouse gas emissions in analogy to the labeling of electricity at EU level.

4.6 Drivers

4.6.1 Environmental integrity and health improvements

Drastic reductions in local air pollutants, greenhouse gas emissions and noise levels are a top priority in national and international politics. The transport sector so far gives the smallest contribution to the reduction of greenhouse gas emissions.

Alternative powertrains and fuels offer the potential to reduce greenhouse gas and pollutant emissions in the transport sector to zero in the long-term. Recognizable effects require a lead time of 15 to 20 years.

Rating

Pre-eminent driver

4.6.2 Energy security and supply

The availability of mineral oil and natural gas will start to decline on a global scale in the foreseeable future, leading to persistently increasing prices as the gap between supply and demand grows.

In addition, fossil energy resources in future will be increasingly concentrated in a smaller number of countries – creating the potential for geo-political and price instability. Hydrogen opens access to a broad range of primary energy sources, including fossil fuels, and increasingly renewable energy sources (e.g. wind, solar, ocean, biomass and geothermal), as they become more widely available.

Thus the availability and price of hydrogen as a carrier should be more stable than any single energy source. The introduction of hydrogen as an energy carrier, alongside electricity, would enable Europe to exploit resources that are best adapted to regional circumstances.

Rating

Pre-eminent driver

4.6.3 Fuel cells are a basic technology innovation promising major advantages

Fuel cells are a basic technology innovation allowing for new and advanced products and services. Being at the forefront of technological development represents a competitive advantage for companies and research institutions. The potential impact of this innovation is comparable to the invention of the transistor and the micro chip in information technology, which has led to personal computers and mobile phones having drastically reshaped professional and private life.

The modularity of fuel cells is a fundamental characteristic that promises much easier adaptation of the technology to other fields of use potentially creating important synergies between mobile, stationary and portable applications. In addition, it allows for a much easier up and down-scaling of the technology to higher or lower power levels significantly reducing development efforts.

Rating

Pre-eminent driver

4.6.4 Economic competitiveness

Development and sales of energy systems are a major component of wealth creation, from automobiles to complete power stations, creating substantial employment and export opportunities, especially for the industrialized nations. European leadership in hydrogen and fuel cells will play a key role in creating high quality employment opportunities, from strategic R&D to production and craftsmen.

In the US and Japan, hydrogen and fuel cells are considered to be core technologies for the 21st century, important for economic prosperity. There is strong investment and industrial activity in the hydrogen and fuel cell arena in these countries, driving the transition to hydrogen – independently of Europe. If Europe wants to compete and become a leading world player, it must intensify its efforts and create a favorable business development environment.

Rating

Major driver

4.6.5 Reconciliation of major goals

Detailed analyses show that promising pathways exist to achieve the goals of climate protection, supply security and increased economic competitiveness at the same time. Hydrogen and fuel cells seem to open the best chances and largest market potentials of all alternatives in the transport sector.

Rating

Major driver (see 4.6.1, 4.6.2, 4.6.3, 4.6.4)

4.6.6 Positive company image

Companies developing and starting to commercialize hydrogen and fuel cells improve the environmental perception of the company by the general public. It demonstrates environmental responsibility, which has become an important factor in the general image of companies.

Some companies have already gone one step further in making environmental compatibility an integral part of the company philosophy, which relates to production processes and to the products alike.

Rating

Major driver

4.6.7 Increased energy efficiency

Hydrogen fuel cell vehicles are significantly more energy efficient than conventional powertrains and thus permit primary energy savings and allow for higher fuel costs for cleaner fuels.

Rating

Major driver (see 4.6.2)

4.6.8 Smooth transition from fossil to renewable

Hydrogen allows for a smooth and gradual transition from 100% fossil to 100% renewable primary energies in the transport sector. This property is unique for hydrogen among all alternative fuels in discussion.

Rating

Major driver

4.6.9 Maximum feedstock flexibility

Hydrogen has the maximum feedstock flexibility and opens many opportunities in its generation and use. It allows many more players and regions to participate in fuel production and it provides many more business opportunities than today’s fuel business.

Rating

Major driver

4.6.10 Additional market for renewable energies

Most renewable energy technologies are restricted to stationary applications; only biomass derived fuels start to enter the transport fuels market. Hydrogen offers for renewable electricity technologies (wind, solar, geothermal, ocean energy etc.) a potential additional market. While renewable energies continue to reduce their generating costs, fossil energies will see a steady cost increase because of availability constraints and growing environmental requirements.

Rating

Minor driver

4.6.11 "All electric car"

There are three tendencies towards an increased use of electricity in cars: increasing electric demand in cars through more electronics, air conditioning etc., the commercial introduction of hybrid cars with electric drive trains, and innovative drive-by-wire concepts (e.g. Hy-Wire by General Motors, Fine-S by Toyota).

Rating

Minor driver

4.7 Literature

[EC 2003] EU roadmap towards a European Partnership for a Sustainable Hydrogen Economy, European Commission, press release, September 10, 2003

[EIHP 2003] www.eihp.org

[EU 2001] White Paper – European transport policy for 2010: time to decide, European Commission, 2001

[EU 2003] Directive 2003/30/EC of the European Parliament and of the Council of 8 May 2003 on the promotion of the use of biofuels or other renewable fuels for transport, OJ L 123/42, 17.5.2003

[HLG 2003] Hydrogen Energy and Fuel Cells – A Vision for our Future, High Level Group for Hydrogen and Fuel Cells, Summary Report, June 2003

[HyNet 2003] www.hynet.info

5 LIFE CYCLE ANALYSIS OF THE ENVIRONMENTAL IMPACTS OF THE SHIFT TO HYDROGEN

The term Life Cycle Analysis (LCA) denominates the comprehensive analysis of the environmental impact caused by a product during its life cycle, comprising its production, use and disposal/ recycling.

An LCA has to cope with a number of difficulties mainly related to the non-availability, uncertainty or variability of data. During recent years, extensive analyses carried out have led to rather well consolidated LCA results for hydrogen fuel cell cars compared to advanced conventional cars.

The values for fuel production and supply depend significantly on the primary energy input used for fuel consumption.

Uncertainties in the fuel consumption values of future advanced conventional and alternative powertrain cars are larger than uncertainties in the Well-to-Tank fuel supply values. Vehicle manufacturing contributes with 10%-15% to the overall emissions of advanced conventional cars. Fuel cell cars will have slightly higher absolute values.

In the mid-term (2010-2020) hydrogen fuel cell cars will allow for reduced greenhouse gas emissions compared to advanced conventional cars including hybrid designs. Hydrogen from natural gas will reduce emissions by 15%-40%, hydrogen from renewable energies by 70%-85%, with the remaining 15%-30% stemming from car manufacturing and from building the fuel supply infrastructure.

Hydrogen fuel cell cars will have comparable energy use values over the entire fuel production, supply and use chain including car manufacturing as advanced conventional cars. Higher energy losses in the fuel production are compensated by the higher fuel efficiency of fuel cell cars.

For ships and airplanes, hydrogen propulsion is not significantly more efficient than conventional propulsion. Greenhouse gas emissions are higher for hydrogen from fossil energies, but 90% lower than those of conventional fuels for hydrogen from renewable energies.

Hydrogen is mainly discussed as a fuel for road transport. This will therefore be the main focus in this chapter. Hydrogen fuel for ships and airplanes will be discussed briefly at the end of the chapter.

Several detailed studies have been undertaken during recent years on the Well-to-Wheel emissions of conventional and alternative fuels and vehicle propulsion concepts. The two most important studies published are a study by General Motors and L-B-Systemtechnik in cooperation with BP, ExxonMobil, Shell and TotalFinaElf [GM-WTW 2002], and a study by the Massachusetts Institute of Technology [MIT 2003]. Further major work is nearing completion in co-operation between CONCAWE, EUCAR and the Joint Research Centre of the European Commission with LBST performing the Well-to-Tank analysis, and Institut Français du Petrole performing the Tank-to-Wheel analysis.

Well-to-Tank values presented in this chapter are LBST analyses using LBST's proprietary *E^2 database* data base and analysis tool. Results are based on [GM-WTW 2002], and on experience gained in detailed work for the CONCAWE-EUCAR-JRC project, the German Transport Energy Strategy and further projects. Tank-to-Wheel values are mainly based on the MIT study [MIT 2003] including a comparison of these values to the GM results [GM-WTW 2002]. Values for vehicle manufacturing are based on [MIT 2003], which are compared to values extracted from [Pehnt 2002].

The focus of this analysis is on the comparison of hydrogen used in fuel cell passenger cars to conventional fuels used in advanced conventional powertrains. Hybrid propulsion is considered for both fuel cells and internal combustion engines.

5.1 Introduction

The term Life Cycle Analysis (LCA) denominates the comprehensive analysis of the environmental impact caused by a product during its life cycle, comprising its production, use and disposal/ recycling.

Environmental impacts are mainly caused by the consumption and/ or transformation of materials and energies. Therefore LCA looks at material flows, energy use and associated emissions (especially greenhouse gas emissions – GHG).

Costs are not an issue within an LCA, but are discussed in chapter 6 of this report.

An LCA of hydrogen fuel has to analyze material flows, energy flows and emissions, caused by

(1) the production of the fuel supply infrastructure and of the vehicles,

(2) the production of the hydrogen fuel and its supply to the user,

(3) the use of the fuel (therefore the vehicle has to be included in the analysis),

(4) the dismantling and disposal or recycling of supply infrastructure and vehicles.

Topics (2) and (3) are addressed in Well-to-Tank and in Tank-to-Wheel analyses, sometimes topics (1) and (4) are partly or fully included. In the present report, topics (1) to (3) will be taken fully into account, topic (4) "recycling" will only be considered for the platinum group metal catalysts in PEM fuel cell stacks.

An LCA has to cope with a number of difficulties, such as

- relevant data are uncertain and may vary to some extent, or are not available in some cases,
- some technologies considered are still under development,
- it is not always clear, where to draw the boundary for the analysis; also there is the problem of by-products and credits,
- there is practically an infinite number of possible fuel pathways, but only few make sense (which then is already a result of the LCA).

But despite the theoretical and practical limitations of an LCA, this is the best method available to assess and compare different energy systems.

An LCA will always be work in progress as technologies are in constant evolution. But it supports the understanding of energy systems and gives orientation where to look for the more sustainable solutions.

5.2 Life cycle analysis (Well-to-Wheel)

For the present analysis, best available technology has been assumed for a timeframe of 2010-2020. This means that a number of assumptions have been made about the technologies involved. In general it has been assumed that all foreseeable technological advances will actually be realized.

Figure 5-1 presents the overall greenhouse gas emissions of advanced conventional and hydrogen fuel cell cars. This summarizes the fuel production and supply paths (Well-to-Tank, see 0), the car operation (Tank-to-Wheel, see 5.4) and the car manufacturing (see 5.5). For car manufacturing and car operation, values are taken from [MIT 2003], values of the fuel supply paths are based on LBST analyses.

The greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) are summarized as CO_2-equivalent weighted by their relative greenhouse effect.

Figure 5-1: Well-to-Wheel greenhouse gas emissions of advanced conventional and of hydrogen fuel cell cars.

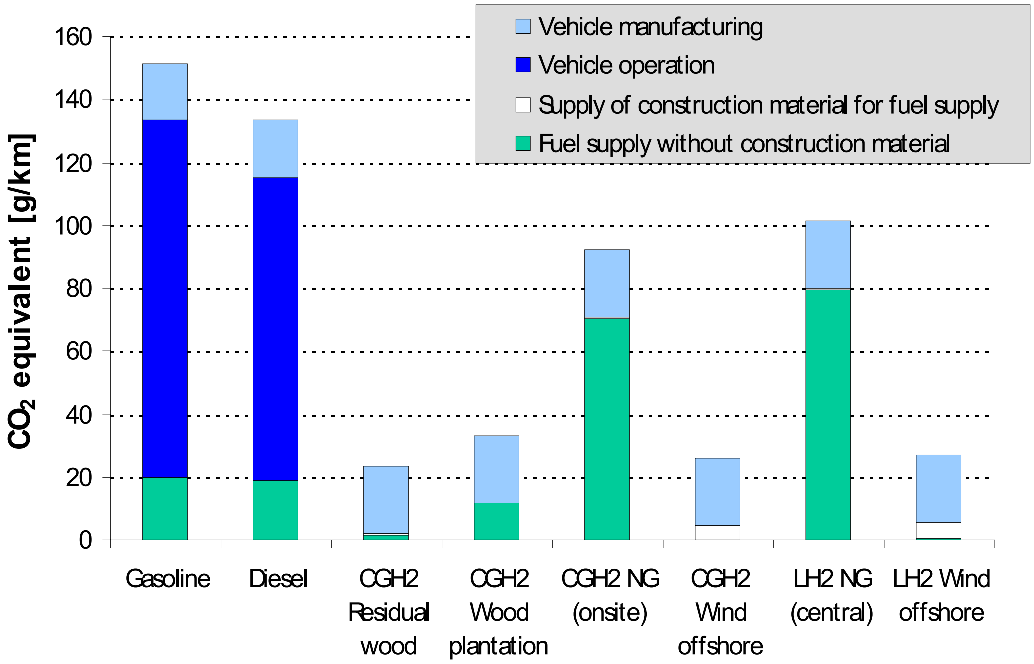
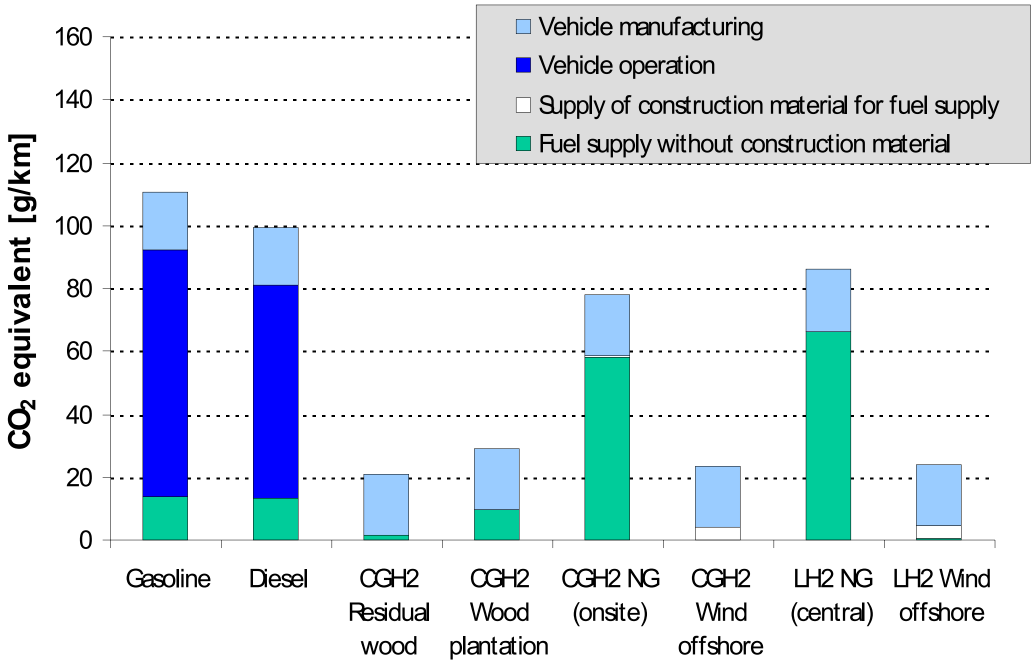


Figure 5-2: Well-to-Wheel greenhouse gas emissions of hybrid cars.



For advanced conventional cars, fuel supply and car manufacturing contribute to the overall greenhouse gas emissions with 10%-15% each, while 79%-80% stem from car operation.

Greenhouse gas emissions of hydrogen fuel cell cars are 15%-25% of the values for advanced conventional cars in case hydrogen is produced from renewable energies. The major contribution stems from car manufacturing, while fuel production and supply infrastructure has a minor contribution. Producing hydrogen from natural gas for use in fuel cell cars allows to reduce greenhouse gas emissions by 25%-40% compared to advanced conventional cars. This is due to the higher efficiency of fuel cell cars and the lower carbon content of natural gas compared to gasoline/ diesel, and partly compensated by the energy losses in natural gas reforming.

Hybridizing conventional and fuel cell powertrains further reduces car fuel consumption, and thus overall greenhouse gas emissions. By hybridization, conventional powertrains gain more in efficiency than fuel cells, reducing the emissions advantage of the latter (see Figure 5-2) to 15%-30% for hydrogen from natural gas.

Figure 5-3: Well-to-Wheel energy use of advanced conventional and of hydrogen fuel cell cars.

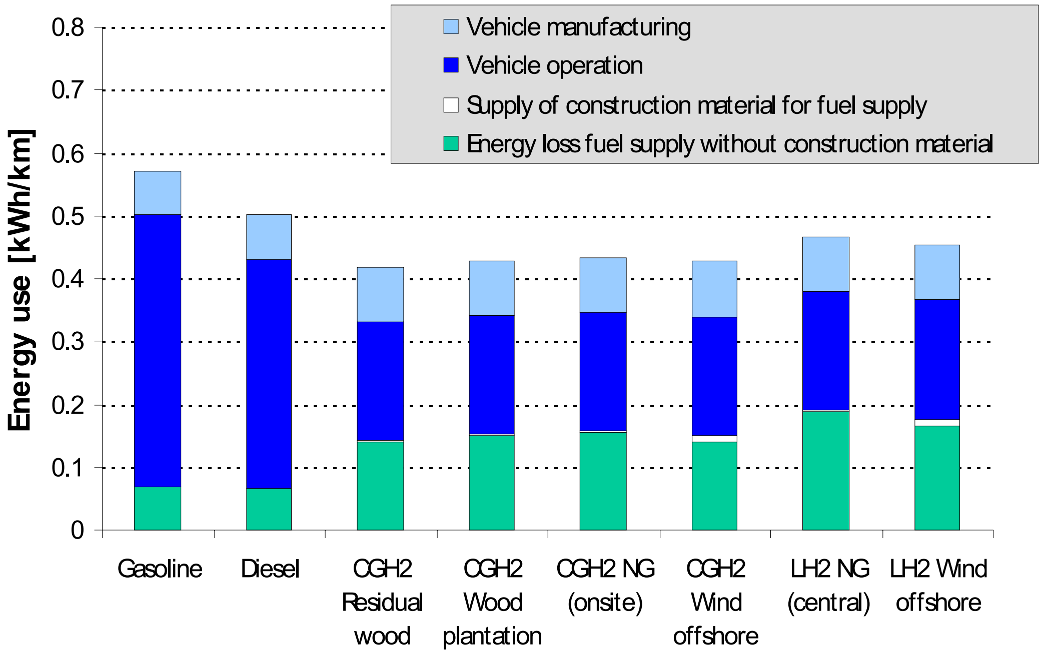


Figure 5-3 presents the values of energy use over the entire production, supply and use chain, which correspond to the emissions in Figure 5-1. Hydrogen fuel cell cars have slightly lower overall energy use values than advanced conventional cars. Taking into account the uncertainties involved in many of the data used for the analysis, the energy uses may as well be slightly above the conventional values for hydrogen fuel cell cars.

5.3 Hydrogen supply paths (Well-to-Tank)

Fuel supply paths include all steps of primary energy production or extraction, conditioning, transport and distribution. For gasoline and diesel this is crude oil extraction, transportation to the refinery, the refining process, transport to the filling station and dispensing. For hydrogen, many pathways may be considered, from fossil primary energies, from renewable energies or from nuclear power. Hydrogen may be produced onsite, i.e. at the filling station, or in a large, central facility and transported to the filling station.

Values presented here are based on LBST analysis building on detailed work in the project [GM-WTW 2002], and on experience gained in detailed work for the CONCAWE-EUCAR-JRC project, the German Transport Energy Strategy and further projects.

Figure 5-4: Greenhouse gas emissions of fuel supply to passenger cars.

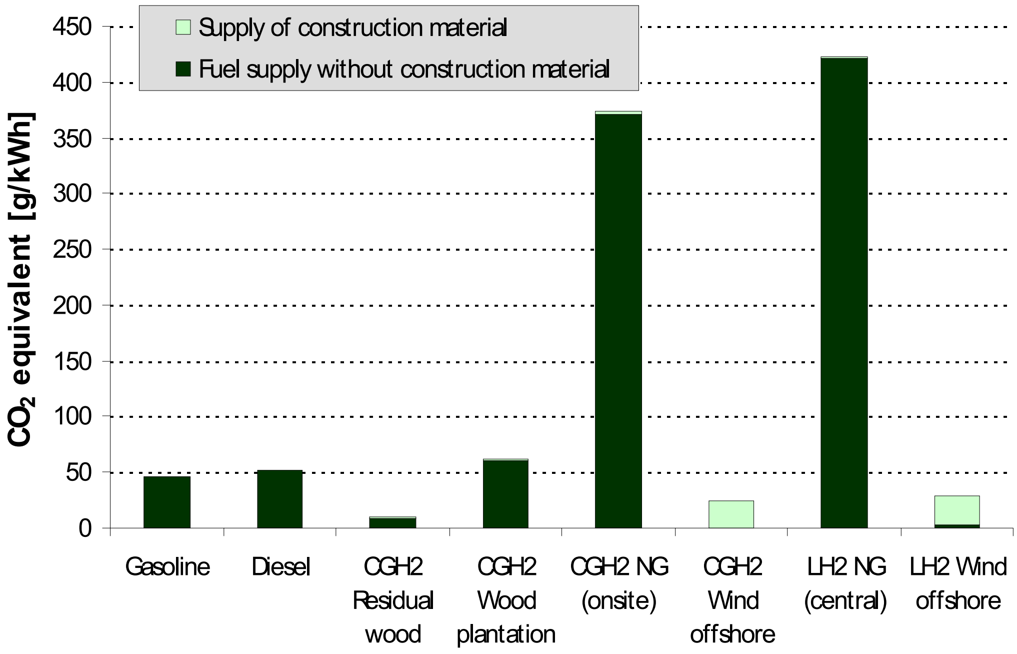


Figure 5-4 presents greenhouse gas emissions of fuel supply to passenger cars. Included are the conventional supply paths for gasoline and diesel as well as various hydrogen supply paths.

- Biomass gasification to compressed gaseous hydrogen using residual wood or dedicated wood plantations,

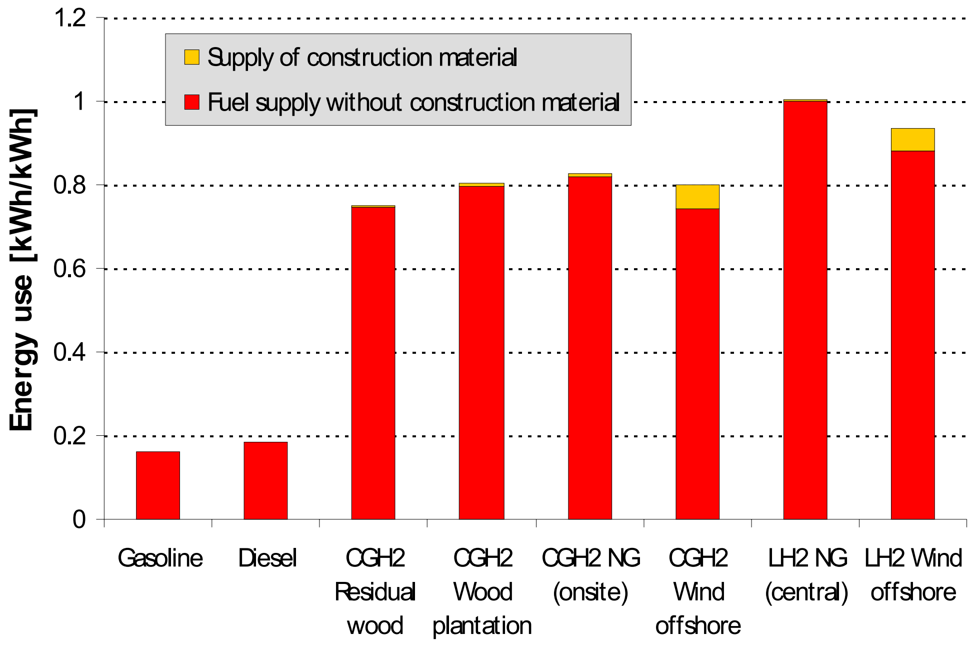
- Onsite natural gas reforming to compressed gaseous hydrogen,
- Onsite electrolysis to compressed gaseous hydrogen using offshore wind power,
- Centralized natural gas reforming to liquid hydrogen with trailer transport to the filling station,
- Centralized electrolysis to liquid hydrogen using offshore wind power with trailer transport to the filling station.

Greenhouse gas emissions of gasoline and diesel extraction, production and supply (excluding the combustion in the car) are 46 and 52 g/kWh, respectively, including the supply of construction materials for the refinery, the tanker ship etc. For hydrogen production and supply, the values are 10-62 g/kWh for the renewable paths, and 374-423 g/kWh for the natural gas paths. The relatively high value for hydrogen from dedicated wood plantation stems from nitrous oxide (N_2O) emissions during plantation caused by nitrogen containing fertilizers. In most cases, supply of construction material for the infrastructure gives a very small contribution to the overall Well-to-Tank emissions. In the case of offshore wind power, the absolute value is still small (25 g/kWh), but represents 100% of the emissions, or close to it.

Figure 5-5 presents the corresponding values for energy use. The graphic reads as follows: Per kWh of hydrogen filled into the car storage tank, 0.8 kWh are spent for the production of hydrogen from wood plantation and its supply to the car.

Energy use for hydrogen supply varies between 0.75 kWh/kWh (CGH_2 from wood plantation) and 1.0 kWh/kWh (LH_2 from natural gas reforming), corresponding to an efficiency of 57%-50%. Energy use for gasoline and diesel extraction, production and supply are 0.16 and 0.18 kWh/kWh, respectively.

Figure 5-5: Energy use of fuel supply to passenger cars.



Results for Well-to-Tank greenhouse gas emission and energy use values are relatively well consolidated internationally, as long as similar assumptions are made.

5.4 Vehicle fuel consumption (Tank-to-Wheel)

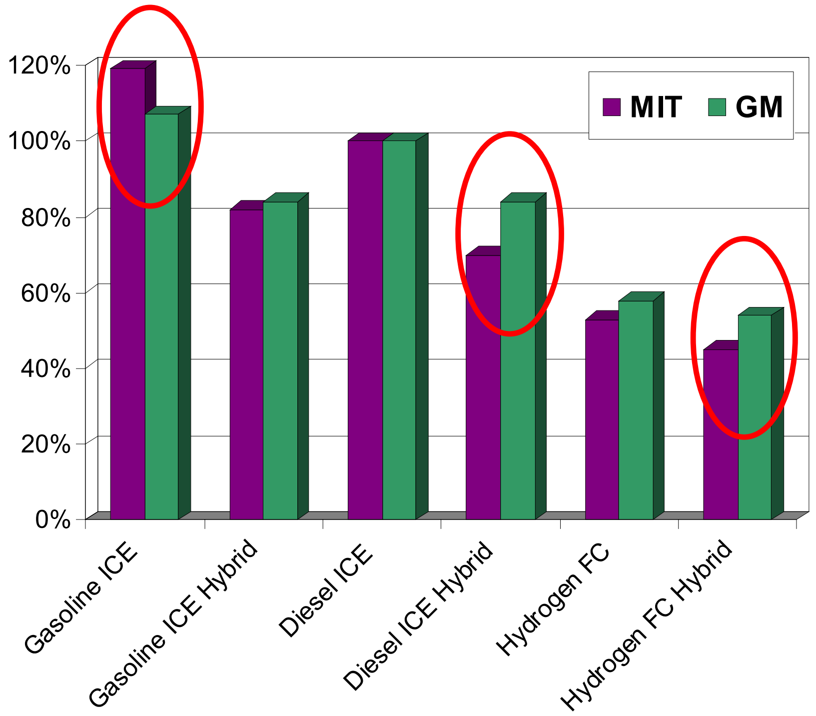
Major analysis published recently are the GM Well-to-Wheel study [GM-WTW 2002] and the study by the MIT [MIT 2003]. Fuel consumption levels are analyzed to be available commercially by 2010 (GM) or 2020 (MIT). Table 5-1 gives an overview of the fuels and propulsion concepts analyzed by the two studies. A good overview of earlier analyses is given by [LBST 2002].

Figure 5-6 compares the fuel consumption values given by the two studies. As they are based on different types of passenger cars driven on different driving cycles, relative values compared to the diesel car are presented. It becomes obvious that both studies mainly differ in the assessment of hybrid powertrains with MIT achieving lower consumption values for hybrid powertrains than GM. In the non-hybrid drive trains, the results of both studies are very similar with the exception of advanced gasoline cars. GM expects direct injection gasoline cars to come rather close to diesel cars in consumption with a 7% penalty only. Figure 5-7 presents the absolute consumption values.

Table 5-1: Overview of combinations of fuel and propulsion system analyzed in [GM-WTW 2002] and [MIT 2002].

	IC engine	IC engine hybrid	Fuel cell	Fuel cell hybrid
Gasoline	GM – MIT	GM – MIT	GM – MIT	GM – MIT
Diesel	GM – MIT	GM – MIT		
Synthetic diesel	GM	GM		
CNG	GM	GM		
Methanol			GM	GM
Ethanol			GM	GM
Hydrogen	GM	GM	GM – MIT	GM – MIT

Figure 5-6: Comparison of relative fuel consumption values for gasoline or diesel engine cars, hydrogen fuel cell cars, and hybrid variants thereof [GM-WTW 2002], [MIT 2003].

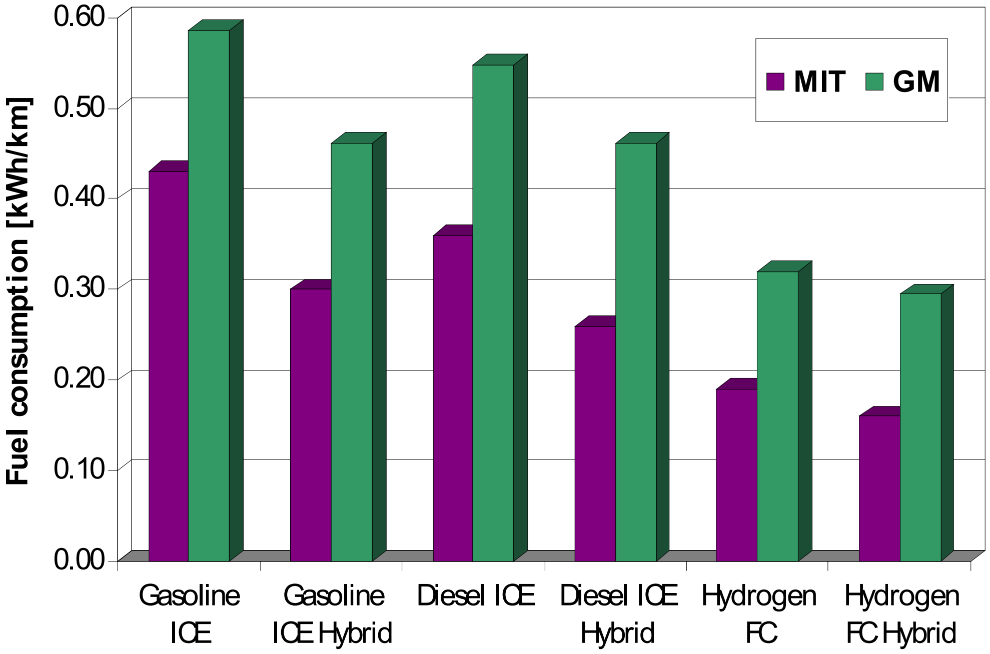


The results show that diesel cars will retain an efficiency advantage over gasoline cars (GM: 7%, MIT: 19%), and that hydrogen fuel cell cars will have a dramatic efficiency advantage of 46%-56% over gasoline cars and of 42%-47% over diesel cars (lower values for GM, higher values for MIT). [LBST 2002] analyzing earlier studies expects hydrogen fuel cell cars to be 40% more efficient than gasoline cars and 32% more efficient than diesel cars in the timeframe 2010-2020.

Hybridizing the powertrains reduces consumption by 20%-30% for diesel engine cars, by 21%-31% for gasoline cars and by 9%-15% for hydrogen fuel cell cars (lower values for GM, higher values for MIT) reducing the efficiency advantage of fuel cells over conventional powertrains.

Until 2010, GM expects an efficiency gain of conventional gasoline cars of 6% compared to 2002, and of 19% for a direct injection gasoline car. Until 2020, MIT expects an increase in efficiency of conventional gasoline cars of 38% compared to 2001. [LBST 2002] analyzing earlier studies expects an efficiency increase of gasoline cars of 31% in the timeframe 2010-2020.

Figure 5-7: Fuel consumption of a typical US mid-size family sedan [MIT 2003] and of an Opel Zafira Minivan [GM-WTW 2002] with different advanced powertrains.



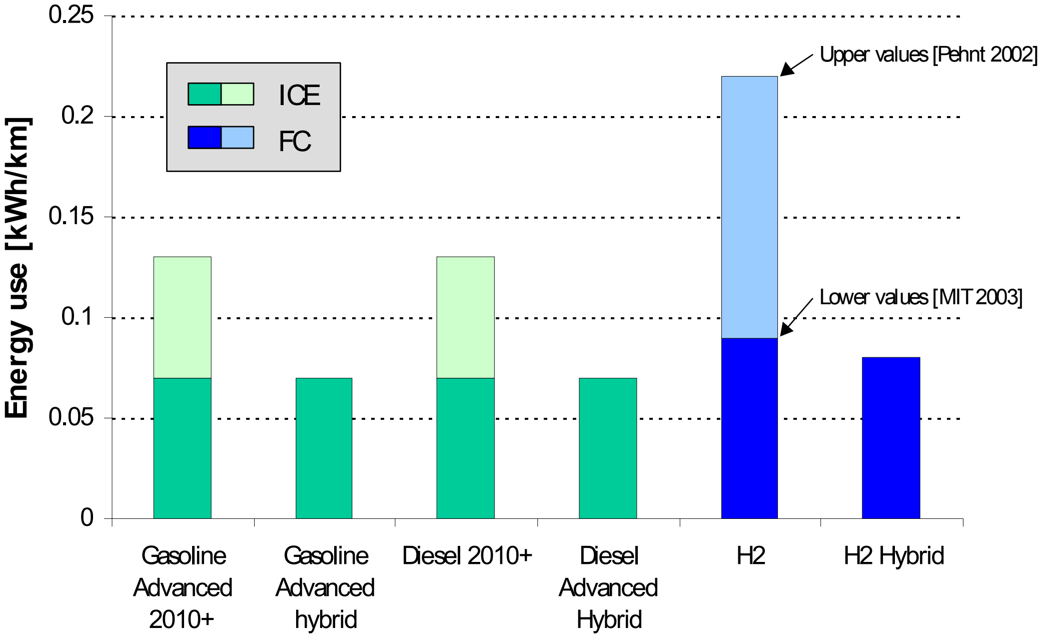
Carbon dioxide emissions of vehicle operation without considering the fuel supply path are 264 g/kWh for both gasoline and diesel, and zero for hydrogen. Multiplying this value with the fuel consumption give the CO_2 emissions per kilometer driven.

The present analysis shows that uncertainty in the fuel consumption values of future advanced conventional and alternative powertrain cars are markedly larger than uncertainties in the Well-to-Tank fuel supply values.

5.5 Vehicle manufacturing

Energy use and greenhouse gas emissions of car manufacturing are included in the Well-to-Wheel analysis of [MIT 2003] and have been analyzed in detail by [Pehnt 2002]. Results are presented in Figure 5-8 and Figure 5-9. A good overview of earlier analyses is given by [LBST 2002], including an assessment of weight reduction potentials through lightweight designs.

Figure 5-8: Energy use for car manufacturing [MIT 2003], [Pehnt 2002].



[MIT 2003] analyzes a typical US mid-size family sedan with a mass of 1458 kg for 2001 and 1150-1250 kg for 2020 for combustion engines, and 1250-1400 kg for hydrogen fuel cells, including 136 kg payload. [Pehnt 2002] analyzes a lower middle-sized class car for 2010 with a mass of 1030-1090 kg for combustion engines, and 1350 kg for hydrogen fuel cells, including driver.

[LBST 2002] comes to the conclusion that lightweight car designs induce higher energy requirements for car manufacturing, which could be offset by dedicated recycling of the lightweight materials used (aluminum, magnesium and fiber composite materials). Aluminum forging alloys used in car manufacturing for example are specific to this application and cannot be produced from mixed aluminum recycling.

While energy requirement assessments differ by a factor of two (see Figure 5-8), greenhouse gas emissions are rather close together, except for fuel cell cars. This reflects the higher greenhouse gas emissions per unit of final energy in North America.

Figure 5-9: Greenhouse gas emissions of car manufacturing [MIT 2003], [Pehnt 2002].

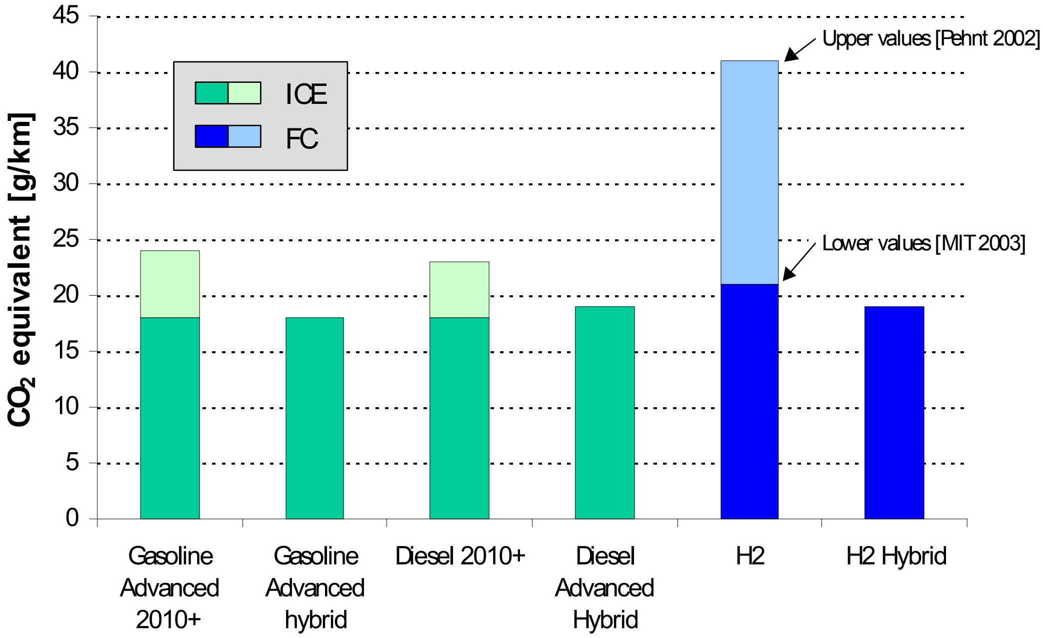
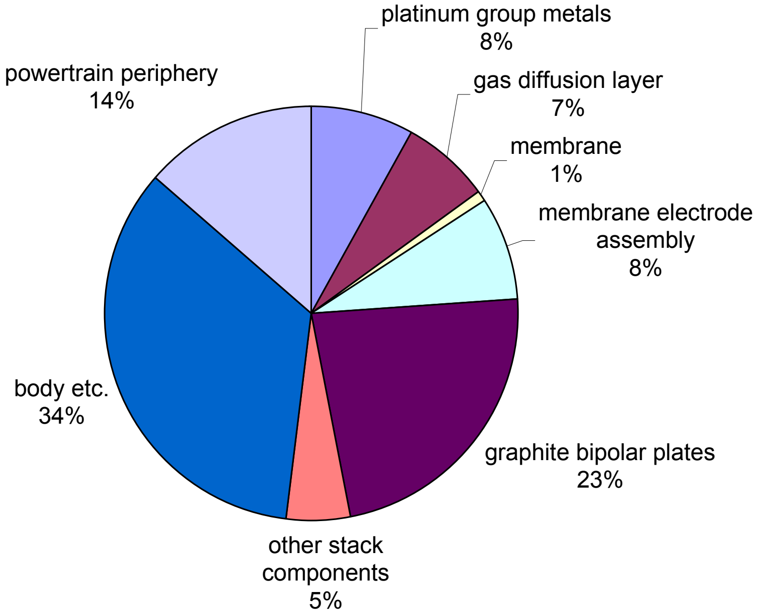


Figure 5-10 shows the breakdown of greenhouse gas emissions for the manufacturing of a hydrogen fuel cell car [Pehnt 2002], which corresponds to the upper value in Figure 5-9. Graphite bipolar plate manufacturing dominates the emissions of fuel cell stack manufacturing with 44%, or roughly one quarter of overall emissions for manufacturing of the entire car. This is mainly due to the high emissions for graphite production. The stack itself represents half the emissions for car manufacturing. Platinum group metals used as electro-catalysts in the fuel cell stack have a relatively small share of the emissions, as recycling is assumed in the analysis. For the European case the breakdown of greenhouse gas emissions and of energy requirements is very similar.

It has to be emphasized that the two analyses referenced here rely on existing data or data assumed for the future. This is subject to rather high uncertainty at present. [Pehnt 2002] assumes graphite bipolar plates, while communications of large car manufacturers and fuel cell developers directly or indirectly hint at metal bipolar plates being the technology of choice for cars. [Pehnt 2002] additionally assumes a platinum load of 0.3 mg/cm², which for a 75 kW fuel cell stack corresponds to about 64 g in total[1]. This is a factor of 20 higher than the platinum contained in a catalytic converter of a conventional gasoline engine, and does not allow to achieve the cost goals for mass produced fuel cell stacks.

[MIT 2003] assumes energy requirements for car manufacturing and related greenhouse gas emissions which differ only insignificantly for internal combustion engine cars, and which are up to 25% higher for hydrogen fuel cell cars.

Figure 5-10: Breakdown of greenhouse gas emissions for hydrogen fuel cell car manufacturing; recycling of platinum group metals is assumed [Pehnt 2002].



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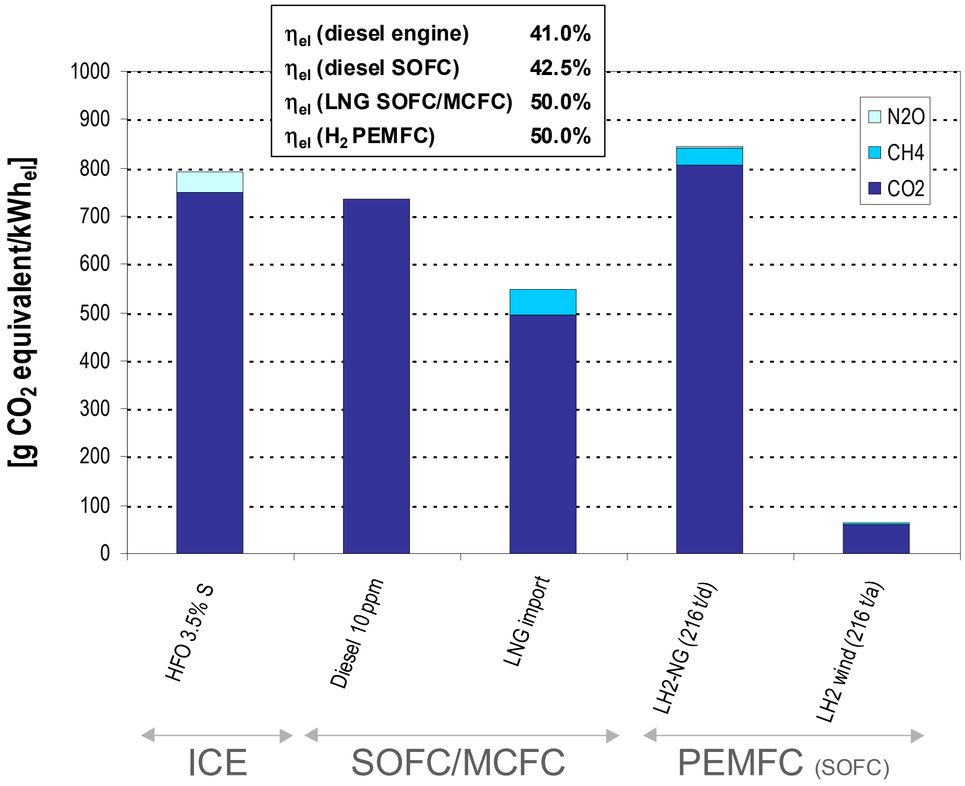
[1] It is assumed that the 0.3 mg/cm² refers to one electrode. In case it refers to both electrodes in one cell, the total platinum load of the stack reduces to 32 g [Pehnt 2002].

5.6 Ships and airplanes

Life cycle analyses for ships and airplanes are carried out in much the same way as for passenger cars. Nonetheless, there is a fundamental difference: hydrogen propulsion technologies are in general not significantly more efficient than the conventional technologies.

For ships this is due to the fact that large ship diesel engines achieve efficiencies of up to 50%, while high temperature fuel cells, possibly combined with gas turbines, still have to demonstrate theoretical efficiencies of 60% or even higher.

Figure 5-11: Greenhouse gas emissions of ship propulsion or onboard power supply of 2 MW_e.



In large airplanes, gas turbines are used for propulsion using kerosene today, and future concepts of hydrogen airplanes include gas turbine propulsion using hydrogen. In high altitudes, not only carbon dioxide is an important greenhouse gas, but also NO_x, water vapor, condensed water (condensation trails) and soot; NO_x and SO_2 aerosols on the other hand reduce the greenhouse effect. The net effect is still subject to some scientific uncertainty, but is certainly larger than the effect of the emitted CO_2 alone. Hydrogen used as airplane fuel would reduce the greenhouse effect of cruising, while the total effect depends on the production of hydrogen.

Figure 5-11 shows the greenhouse gas emissions of ship propulsion or onboard electric power supply of 2 MW_e. While liquefied natural gas (LNG) allows for significant greenhouse gas emission reductions, hydrogen from fossil energies used in fuel cells cannot compensate for the energy losses in hydrogen production. The overall emissions are higher than in the conventional case. Only hydrogen from renewable energies can reduce overall emissions. In this case, reductions are in the order of 90%.

It has to be noted that pollutant emissions of ships using conventional heavy fuel oil are very high. Heavy fuel oil in the EU has an average sulfur content of 3.5%, which causes equivalent SO_2 emissions when burnt.

5.7 Literature

[LBST 2002] Comparison of different propulsion systems in private transport in terms of energy saving and reduction of greenhouse gases, L-B-Systemtechnik, 2002, www.lbst.de/propulsion

[GM-WTW 2002] Well-to-Wheel Analysis of Energy Use and Greenhouse Gas Emissions of Advanced Fuel/Vehicle Systems – A European Study, GM, LBST, BP, ExxonMobil, Shell, TotalFinaElf, 2002, www.lbst.de/gm-wtw

[MIT 2003] Comparative Assesment of Fuel Cell Cars, Massachusetts Institute of Technology, February 2003

[Pehnt 2002] Ganzheitliche Bilanzierung von Brennstoffzellen in der Energie- und Verkehrstechnik, M. Pehnt, VDI Verlag, Düsseldorf 2002

6 ESTIMATION OF COSTS AND FUTURE TRENDS

Major auto companies developing fuel cells have published results of manufacturing cost analyses in the mid-1990ies. The promising results have led to increased development efforts within automotive industry.

Recent analyses for the US Department of Energy come to the conclusion that current PEM fuel cell technology would allow manufacturing costs of $325/kW for automotive fuel cell systems at production volumes of 500,000 units per year. Projected technology advances would allow for a reduction to around $100/kW. The study concludes that further technological advances are required.

The FreedomCAR Partnership between the US Department of Energy and the North-American automotive industry has set a manufacturing cost goal of $30/kW for automotive fuel cell systems for 2015, which represents full competitiveness to internal combustion engines.

Recently, high-level representatives of DaimlerChrysler, Honda and General Motors/ Opel have agreed on a conference that a manufacturing cost goal of $50/kW for the entire fuel cell powertrain including electric drive motors can be achieved at production volumes of several 100,000 to one million cars.

Detailed studies of platinum availability suggest that this should not be a limiting factor in the commercialization of fuel cell vehicles even in the very long-term assuming vehicle fleets several times the present world-wide fleet. This includes the total amount of platinum required as well as the speed of production increase. Achieving low platinum load goals and high recycling levels are key to this as well as to achieving fuel cell manufacturing cost goals.

Hydrogen production and supply costs depend on the industrial context. At present, hydrogen is a chemical commodity, not a transport fuel. Therefore, all cost projections have to be based on a future industrial scenario for hydrogen fuel.

Because of the significantly higher fuel efficiency of hydrogen fuel cell cars, an economic comparison with conventional cars and fuels has to be based on costs per kilometer driven. Hydrogen from natural gas and from biomass in a mass market comes close to full competitiveness with untaxed conventional fuel costs at current crude oil prices. Hydrogen from wind energy can come close to competitiveness at historically high crude oil prices.

Tax reductions similar to the current taxation for natural gas as automotive fuel for example in Germany will enable full competitiveness of hydrogen fuel after an initial market introduction phase. Rising crude oil prices would reduce the need for tax reductions.

For ships and airplanes, hydrogen production and supply costs from fossil energies are markedly higher than conventional costs. Hydrogen from wind energy is 8 to 10 times as costly.

Total cost of ownership of a car has two major elements: the purchase of the car, and the spendings for fuel. As discussed briefly in chapter 7 “Evaluation of the potential for wide scale introduction of hydrogen as a fuel for each mode” there is not necessarily a relation between manufacturing costs and sales prices, neither for cars nor for fuels. Prices are defined by market forces and by company strategies, while manufacturing costs are more subject to scientific evaluation. Therefore, this chapter will focus on manufacturing costs.

Hydrogen fuel for ships and airplanes will be discussed briefly at the end of the chapter.

6.1 Vehicle costs

Fuel cell vehicle costs are a major subject of public discussion. Reliable data, on the other hand, are scarce. Studies by the automotive industry have been made and results published in the mid-1990ies. Since then, fuel cell cars are more and more approaching commercialization, and information about detailed technological advances and manufacturing cost estimates no longer enter the public domain.

Several studies of PEM fuel cell manufacturing costs have been carried out and results published in the mid-1990ies by car industry, fuel cell developers, consultants and research institutes.

A study by Ford and Directed Technologies [DTI 1997], [Ford 1997] accomplished in 1997 reports fuel cell stack production costs of between \$19 and \$27/kW$_{gross}$ for production volumes of 500,000 units. This assumes four different technologies for bipolar plates including metal and graphite plates. Lowest costs were achieved with injection molded composite graphite plates, second best were unitized metallic plates. Stack costs are dominated by MEA costs ranging from 36% to 56% of the total stack manufacturing costs. Bipolar plate fraction ranges from 15% to 29%.

In1995, Daimler-Benz and Siemens have published results of internal studies revealing fuel cell manufacturing costs (most probably referring to systems) of 200 to 400 DM/kW (\$110 to \$220/kW) at production volumes of 100,000 units [DB 1995], [DB 1995-2], [DB 1995-3]. Curves of manufacturing costs over production volumes were presented.

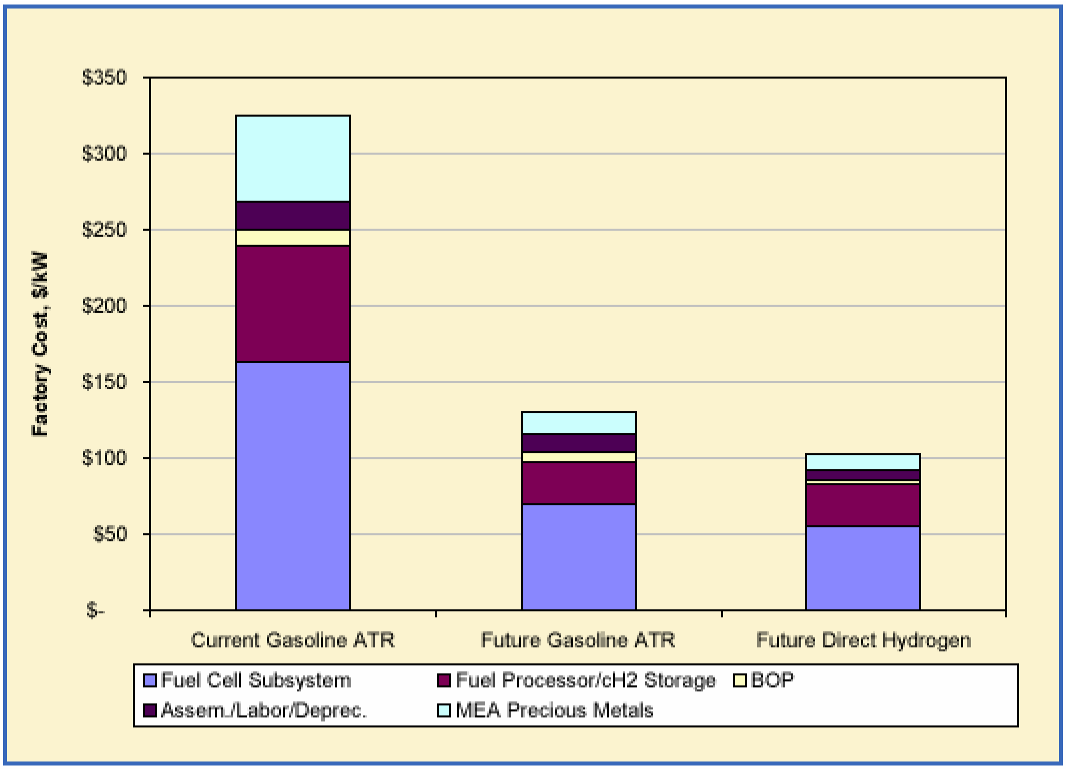
Table 6-1: Early estimates of fuel cell manufacturing costs, allowable costs and cost goals.

	Cost Estimate	Year of study	Comments
General Motors (see [Princeton 1997], [DB 1995-3], [WFCC 1997])	\$46 - \$65/kW	1995	Including methanol reformer
Daimler-Benz [DB 1995], [DB 1995-2], [DB 1995-3]	200 - 400 DM/kW (\$110 - \$220/kW)	1995	H_2 fuel cell system @ 100,000 units
Siemens (see [DB 1995], [DB 1995-2], [DB 1995-3])	300 - 500 DM/kW (\$165 - \$275/kW)	1995	H_2 fuel cell system @ 100,000 units
DTI [DTI 1997], Ford [Ford 1997]	\$19 - \$27/kW$_{gross}$	1997	fuel cell stack @ 500,000 units
Delucchi (see [Princeton 1997])	\$120/kW	1997	H_2 fuel cell system
Chrysler (see [Princeton 1997])	\$200/kW	1997	with current manufacturing technology
Arthur D. Little (see [WFCC 1997])		1995	fuel cell stacks
	\$250/kW		mass production
	below \$50 - \$75/kW		mass production plus implementation of technology improvements already demonstrated in laboratory settings
Allowable costs for heavy transport [DeNora 1997]	\$100 - \$500/kW	1997	fuel cell system; size: 50 - 150 kW
Allowable costs for passenger cars [DeNora 1997]	\$50/kW	1997	fuel cell system; size: 10 - 50 kW
European Union development goal [EC 1997]	200 ECU/kW (\$220/kW)	1997	fuel cell system

A study by Princeton University [Princeton 1997] gives a survey of further cost estimates, which are not directly comparable as some include methanol reformers, but which indicate production costs of between $50 and $100/kW for the fuel cell system.

Arthur D. Little [WFCC 1997] in 1995 estimates manufacturing costs for fuel cell stacks of $250/kW using existing technology in mass production, going down to $50-$75/kW by implementing technology improvements already demonstrated in laboratories (see Table 6-1).

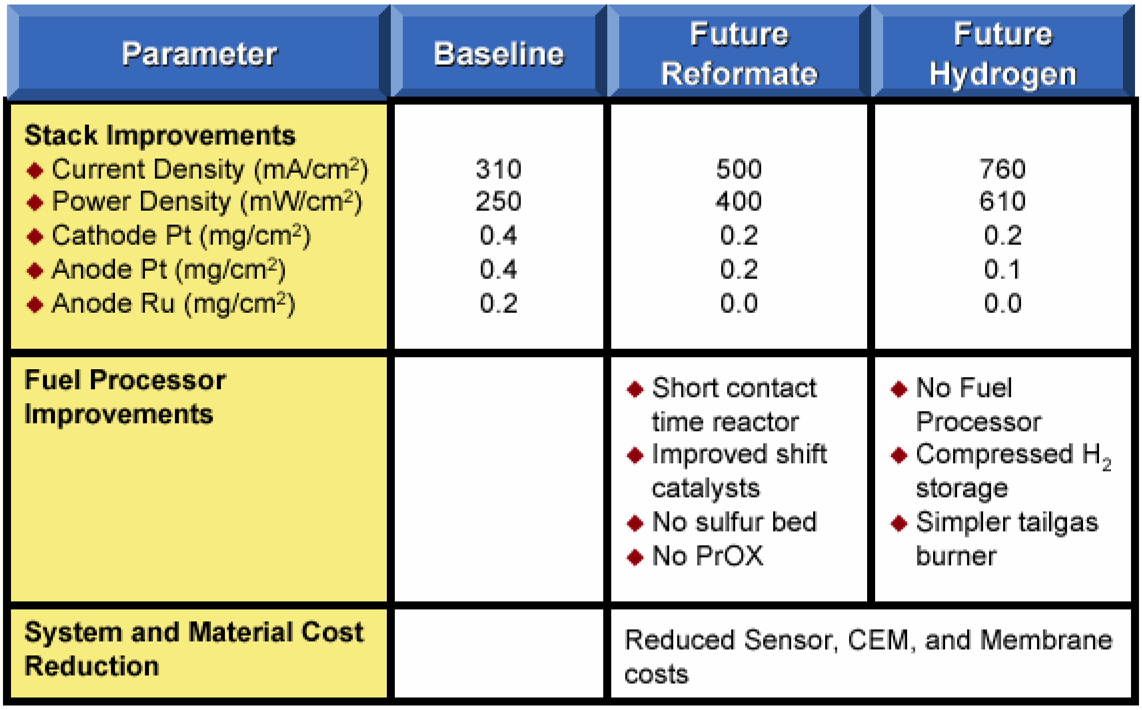
Figure 6-1: Fuel cell system manufacturing costs based on current technology (left) and projected advances for gasoline reformer (ATR) and direct hydrogen systems including CGH_2 storage [TIAX 2003].



Since the late 1990ies publications of cost analyses have become rare. TIAX (formerly Arthur D. Little) has carried out cost analyses for the US-Department of Energy in various steps of refinement during recent years [TIAX 2003], [TIAX 2002], [ADL 2001], [ADL 2000] [ADL 1999].

In 1999, a baseline cost estimate for a 50 kW PEM fuel cell system for passenger cars including a gasoline reformer was developed based on technology available in the year 2000, using a high production volume scenario (500,000 units per year). This model was subsequently refined soliciting feedback from system and component manufacturers. In 2001, the focus was directed to future cost developments based on projected technology. In 2002, an electrochemical model for the relationship between catalyst loading, temperature, pressure, and power density was combined with the cost model in order to understand the tradeoffs between catalyst loading and cost of the stack. The model was extended to direct hydrogen fueled systems.

Figure 6-2: Parameters assumed for the manufacturing cost calculations [TIAX 2003].



Parameter	Baseline	Future Reformate	Future Hydrogen
Stack Improvements ◆ Current Density (mA/cm²) ◆ Power Density (mW/cm²) ◆ Cathode Pt (mg/cm²) ◆ Anode Pt (mg/cm²) ◆ Anode Ru (mg/cm²)	 310 250 0.4 0.4 0.2	 500 400 0.2 0.2 0.0	 760 610 0.2 0.1 0.0
Fuel Processor Improvements		◆ Short contact time reactor ◆ Improved shift catalysts ◆ No sulfur bed ◆ No PrOX	◆ No Fuel Processor ◆ Compressed H_2 storage ◆ Simpler tailgas burner
System and Material Cost Reduction		Reduced Sensor, CEM, and Membrane costs	

The resulting fuel cell system manufacturing costs presented in Figure 6-1 are based on the parameters compiled in Figure 6-2. At current technology, manufacturing costs are around $325/kW in mass production. Projected technology advances allow for a reduction to around $100/kW. [TIAX 2002] comes to the conclusion that the projected costs are still higher than cost goals for commercialization. Further technological advances including medium temperature technology (100-200°C) are required in order to achieve these goals.

Another detailed study of PEM fuel cell system manufacturing costs has been presented by Directed Technologies, USA, in 2002 [DTI 2002]. With present technology, manufacturing costs of a reformer fuel cell system at volumes of 500,000 units per year are estimated at $251/kW$_e$, which is 23% lower than the TIAX estimate. Cost reductions with increasing manufacturing volumes are presented in Figure 6-3. A cost comparison of reformer versus direct hydrogen system excluding hydrogen storage is presented in Figure 6-4.

Figure 6-3: PEM fuel cell system manufacturing cost estimates at various production volumes (2001 technology level) [DTI 2002].

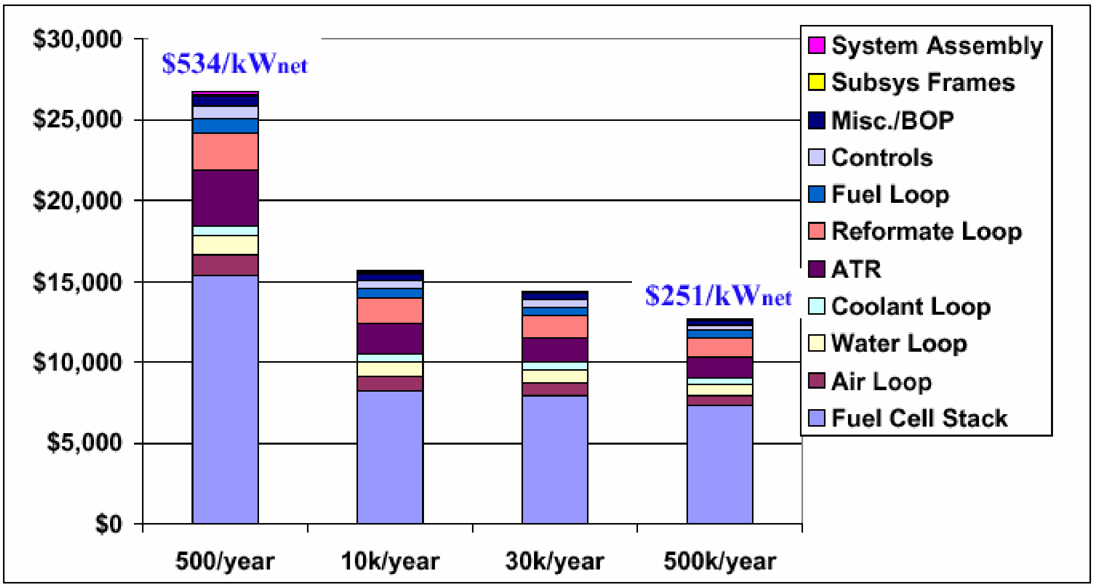
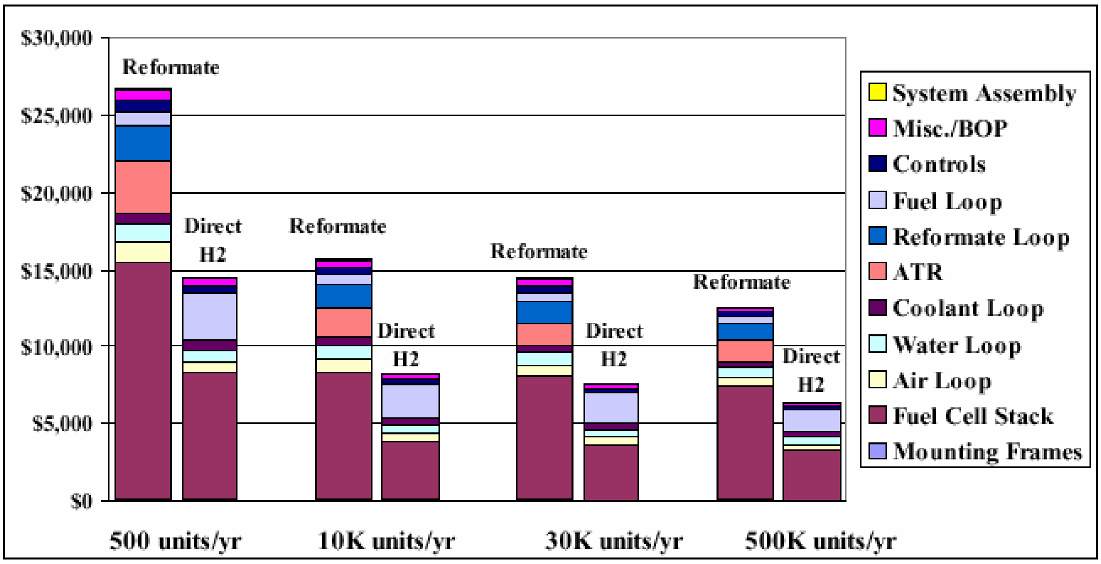


Figure 6-4: Comparison of 50 $kW_{e,\,net}$ reformer and direct hydrogen fuel cell system excluding hydrogen storage (2001 technology level) [DTI 2002].



Platinum loads are a result of the combined electrochemical and cost models in the TIAX approach. Figure 6-5 shows that the fuel cell stack materials costs reach a minimum around a cathode platinum load of 0.2 mg/cm^2. At very low platinum loads non-catalytic materials dominate the costs while at high loads, platinum costs dominate. Around the minimum, both cost factors have similar contributions. The 50 kW 'future hydrogen' system contains a total of 27 g platinum.

Figure 6-5: Fuel cell stack materials costs as a function of the cathode platinum load of the 'future hydrogen' system [TIAX 2003].

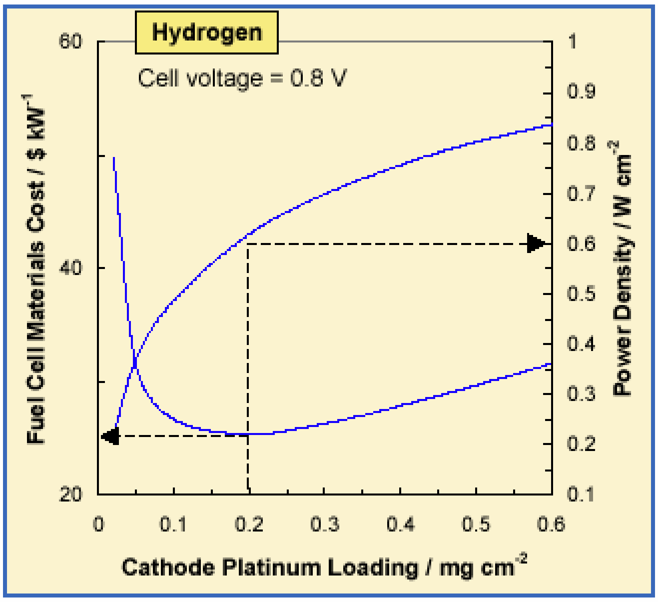
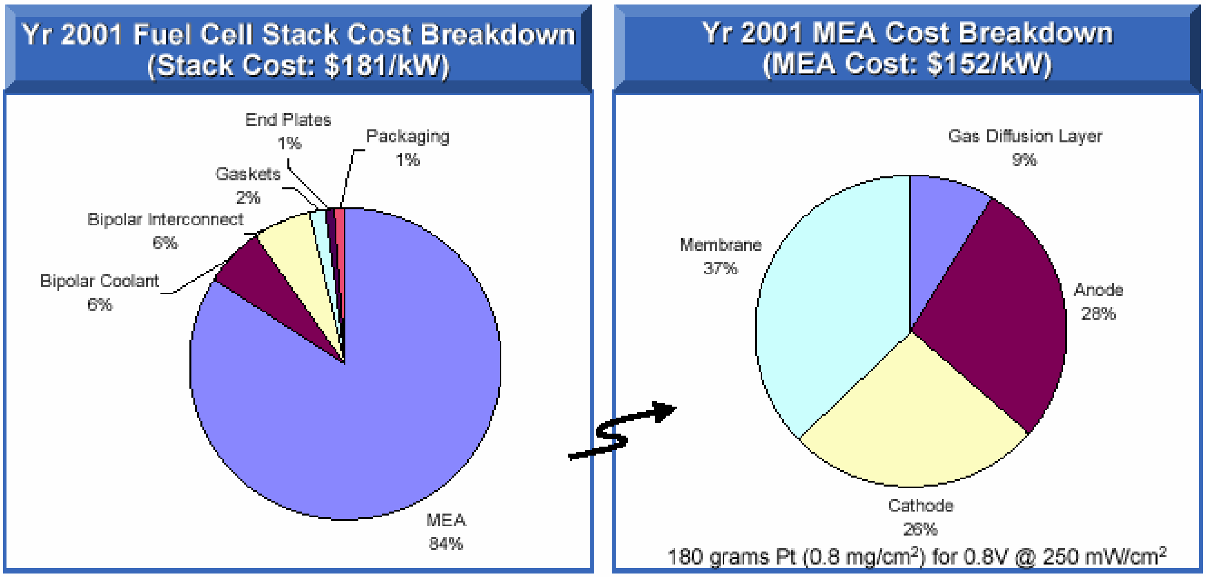


Figure 6-6 shows the fuel cell stack cost breakdown at current technology. The stack costs are clearly dominated by the MEA costs representing 84%. Molded graphite/ polymer composite bipolar plates are assumed.

The fuel cell stack contributes 83% to the system, the stack cooling system 5%, the compressed air supply 9% and the integrated tailgas burner 3% [TIAX 2003].

Figure 6-6: Cost breakdown for fuel cell stacks of present technology [TIAX 2003].



6.1.1 Platinum costs

Figure 6-1 shows that the contribution of the platinum to the overall system of currently 17% is expected to decrease to around 10% in the advanced technology case [TIAX 2003].

Figure 6-7 and Figure 6-8 present the development of precious metal prices during the last seven years. Platinum prices remained around $400 per troy ounce (31.103 g) during 1997 until mid-1999 increasing to $600/tr.oz. until end of 2000. After falling again to just above $400/tr.oz. prices are on a steady increase since the end of 2001 and are around $780/tr.oz. at present.

For current technology, platinum requirements are assumed to be between 137.5 g [DTI 2002] and 180 g [TIAX 2003] for a 50 $kW_{e,\,net}$ PEM fuel cell system. For a future system using best available laboratory results 27 g platinum are assumed by [TIAX 2003], while ultimate goals are around 6.2 g for 50-80 kW systems [AEA 2003]. In comparison, autocatalysts use about 1.6 g platinum and 4.7 g palladium per car[1].

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[1] Palladium is around 4 times cheaper than platinum at present. In contrast, in February 2001, palladium was roughly double as expensive as platinum [www.kitco.com].

Figure 6-7: Development of precious metal prices [DTI 2002].

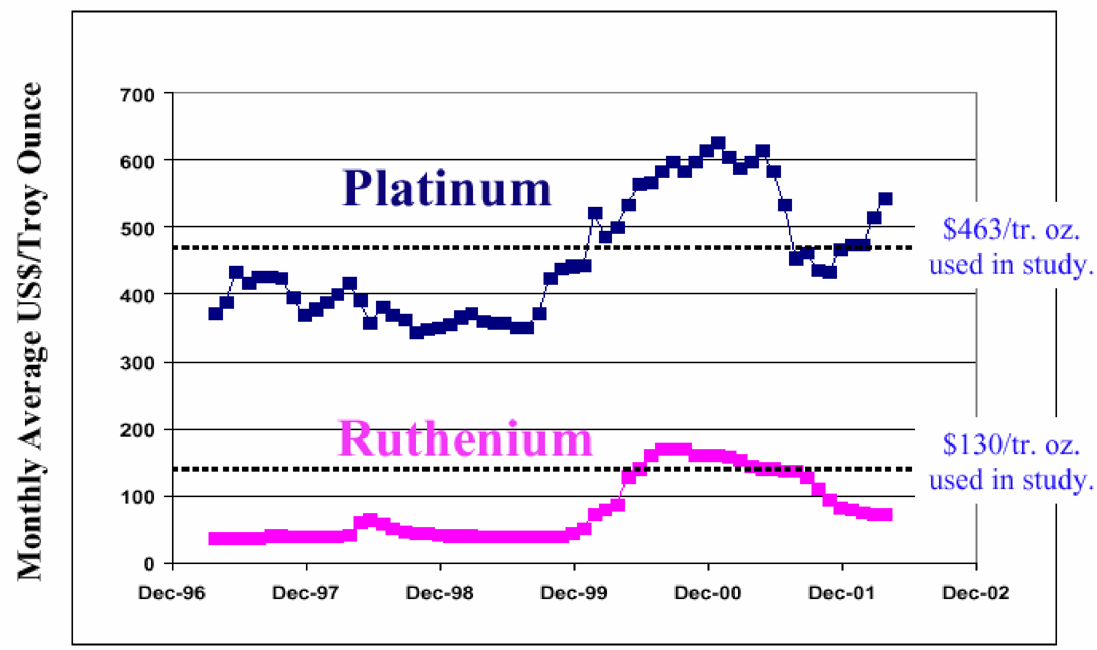
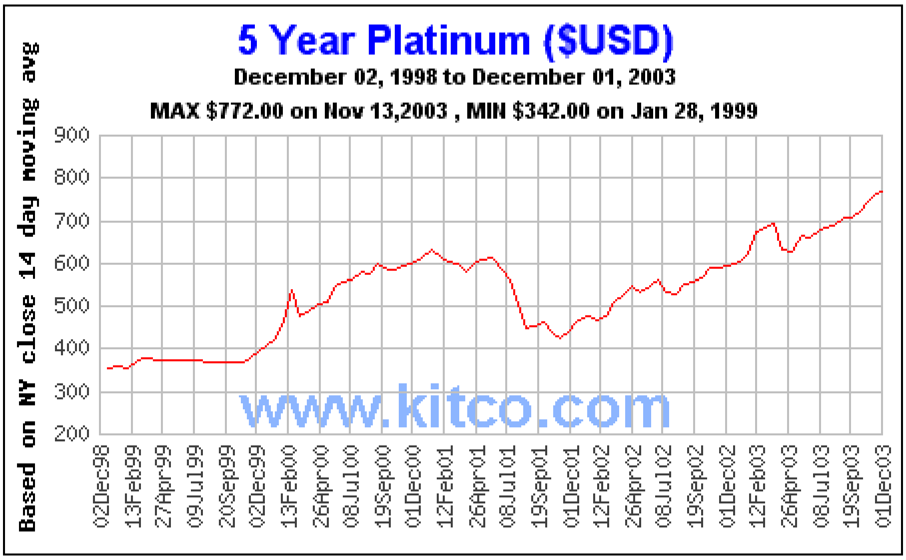


Figure 6-8: Development of platinum prices over the last five years [www.kitco.com].



These figures result in catalyst costs of $45/kW to $100/kW with current technology assuming long-term average or current platinum prices, respectively. For future systems, this would go down to $8.8/kW to $14.9/kW at platinum requirements of 27 g per system, or to $2.0/kW to $3.4/kW.

6.1.2 Platinum availability

Platinum availability for fuel cell vehicles has been analyzed in several detailed studies during recent years [Rade 2001], [ORNL 2001], [AEA 2003].

The main demand sectors for platinum are currently jewellery (41%), autocatalysts (41%), electrical equipment manufacture (6%), chemicals processing (5%) and glass manufacture (5%). The total demand has doubled in the last 20 years and currently stands at 190 t per year [AEA 2003].

Most of the world's platinum supply comes from South Africa (70%) or Russia (22%). Production is increasing and was expected is to outstrip demand in 2002. A study of South African reserves has concluded that there are sufficient accessible reserves to increase supply by up to 5% per year for each of the next 50 years [AEA 2003].

Recycling of platinum from fuel cell stacks is expected to be technically and commercially viable when there is a volume market for fuel cell cars. Processes are being developed and transferred from the laboratory to pilot plant schale. Recycling rates are likely to be up to 98% as it is easier to recycle platinum from a fuel cell stack than from an autocatalyst [AEA 2003].

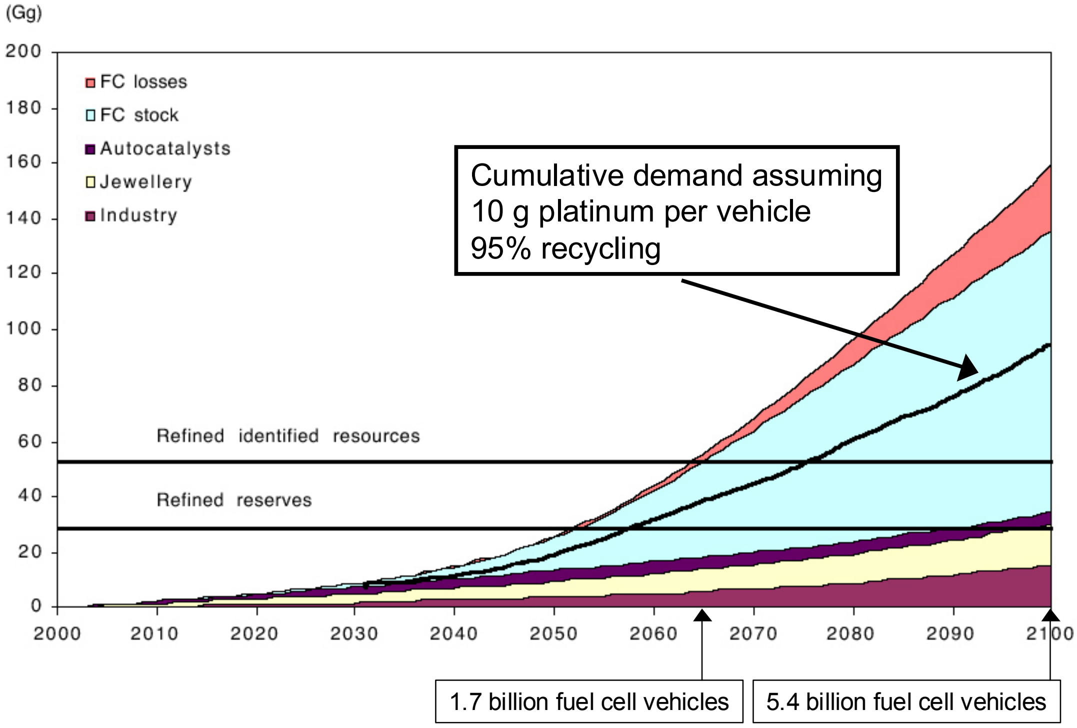
Assuming a platinum requirement of 10 g per vehicle and a future world vehicle fleet of 1 billion units a total of 10,000 t of platinum would be required. Refined identified resources of platinum world-wide are 53,000 t, cumulative platinum production until 2000 was 4,000 t.

[Rade 2001] develops a platinum demand base scenario assuming

- 19 g platinum per fuel cell vehicle,
- 10% recycling losses,
- a fuel cell lifetime of 10 years,
- a total vehicle fleet development reaching 5,405 million vehicles in 2100 from 531 million in 2000 and
- a fuel cell vehicle introduction to start in 2005 with the market penetration modelled as a sigmoidal growth curve based on a logistic model with an inflection point at 2050.

The scenario results are presented in Figure 6-9 and Figure 6-10. The cumulative platinum demand including all demand sectors (jewelry, industry etc.) equals the total refined as to yet identified resources around 2065 at a vehicle fleet of 2.5 billion vehicles, two thirds of which are fuel cell vehicles. Inverting this statement leads to the conclusion that even using conservative assumptions of platinum load and recycling losses platinum resources will allow the build-up of a fleet of 1.7 billion fuel cell vehicles.

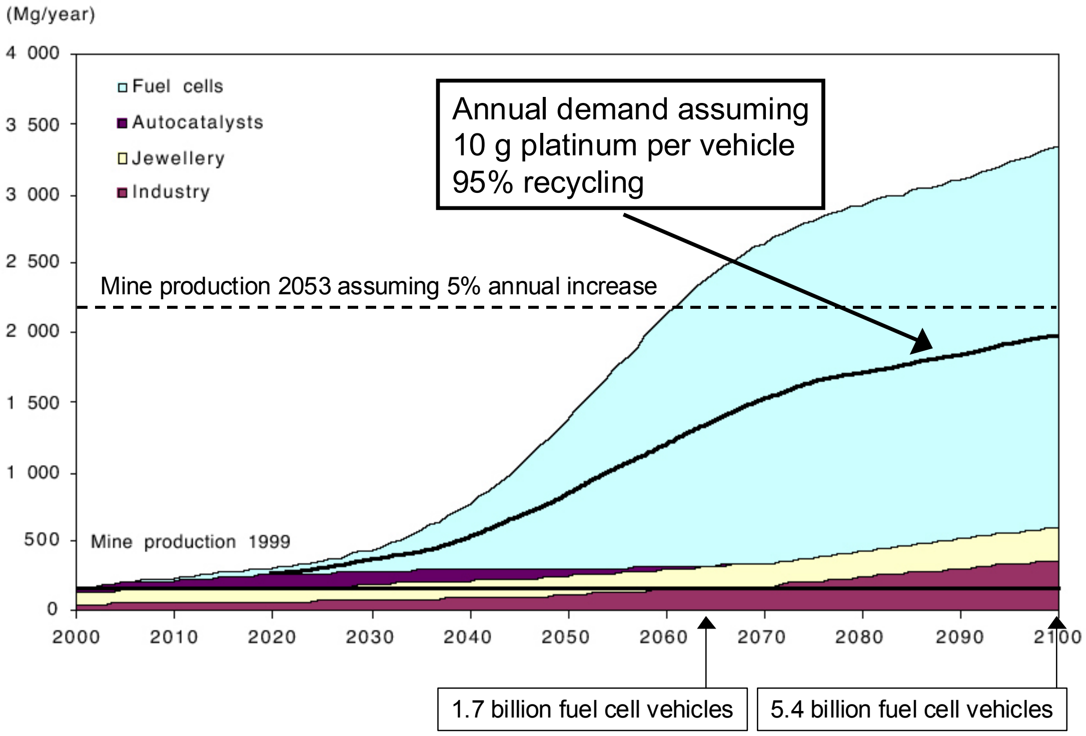
Figure 6-9: Cumulative demand in [1000 t] for primary platinum in the baseline scenario of [Rade 2001], and in a scenario using less conservative assumptions.



Assuming an increase of platinum production by 5% per year over the next 50 years (see above) would result in an 11.5 fold increase in production to 2180 t/a from today's 190 t/a. This annual demand is reached in the base scenario of [Rade 2001] around 2060 indicating that also annual production will not limit the production of fuel cell vehicles until that very long-term timeframe.

Thus, detailed studies of platinum availability suggest that this should not be a limiting factor in the commercialization of fuel cell vehicles even in the very long-term assuming vehicle fleets several times the present world-wide fleet. This includes the total amount of platinum required as well as the speed of production increase. Achieving low platinum load goals and high recycling levels are key to this.

Figure 6-10: Annual demand in [t/a] for primary platinum in the baseline scenario of [Rade 2001], and in a scenario using less conservative assumptions.

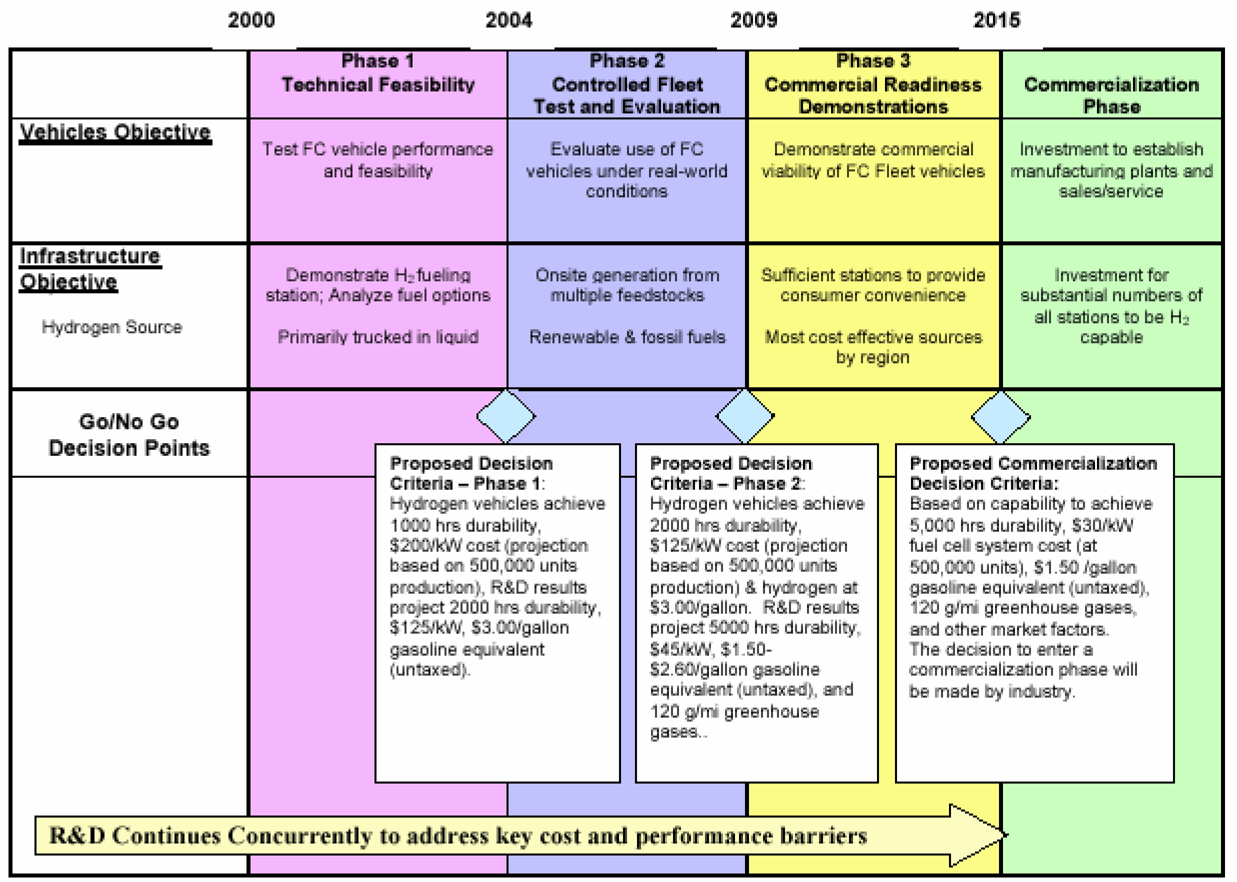


6.1.3 Fuel cell manufacturing cost goals

The US Department of Energy has defined cost goals for their fuel cell development programs. The three phase program leading to the commercialization phase of hydrogen fuel cell vehicles defines cost goals for the transition from each phase to the next [DoE 2003]. For the cost goals, manufacturing volumes of 500,000 units per year based on available technology are assumed. Figure 6-11 shows cost goals of $200/kW for fuel cell systems for 2004, $125/kW for 2009 and $30/kW for 2015, which represents full competitiveness to internal combustion engines.

The FreedomCAR Partnership Plan between the US Department of Energy and the United States Council for Automotive Research representing DaimlerChrysler, Ford and General Motors [FreedomCAR 2003] defines cost goals of $45/kW for fuel cell systems including reformer for 2010, and of $30/kW for 2015, but excluding vehicle traction electronics and electric motors. The cost goal for the electric propulsion system is $12/kW$_{peak}$.

Figure 6-11: US Department of Energy timeline to obtain commercialization of hydrogen fuel cell vehicles [DoE 2003].



2000 2004 2009 2015

	Phase 1 **Technical Feasibility**	**Phase 2** **Controlled Fleet Test and Evaluation**	**Phase 3** **Commercial Readiness Demonstrations**	**Commercialization Phase**
Vehicles Objective	Test FC vehicle performance and feasibility	Evaluate use of FC vehicles under real-world conditions	Demonstrate commercial viability of FC Fleet vehicles	Investment to establish manufacturing plants and sales/service
Infrastructure Objective	Demonstrate H_2 fueling station; Analyze fuel options	Onsite generation from multiple feedstocks	Sufficient stations to provide consumer convenience	Investment for substantial numbers of all stations to be H_2 capable
Hydrogen Source	Primarily trucked in liquid	Renewable & fossil fuels	Most cost effective sources by region	

Go/No Go Decision Points

Proposed Decision Criteria – Phase 1: Hydrogen vehicles achieve 1000 hrs durability, \$200/kW cost (projection based on 500,000 units production), R&D results project 2000 hrs durability, \$125/kW, \$3.00/gallon gasoline equivalent (untaxed).

Proposed Decision Criteria – Phase 2: Hydrogen vehicles achieve 2000 hrs durability, \$125/kW cost (projection based on 500,000 units production) & hydrogen at \$3.00/gallon. R&D results project 5000 hrs durability, \$45/kW, \$1.50-\$2.60/gallon gasoline equivalent (untaxed), and 120 g/mi greenhouse gases..

Proposed Commercialization Decision Criteria: Based on capability to achieve 5,000 hrs durability, \$30/kW fuel cell system cost (at 500,000 units), \$1.50 /gallon gasoline equivalent (untaxed), 120 g/mi greenhouse gases, and other market factors. The decision to enter a commercialization phase will be made by industry.

R&D Continues Concurrently to address key cost and performance barriers

The Japanese Roadmap for polymer electrolyte fuel cell technologies development of May 2003 [FCCJ 2003] specifies current manufacturing costs of fuel cell stacks of \$9155/kW and defines a goal of \$36/kW for 2015.

On the conference “Hessischer Mobilitaetskongress 2003” in Frankfurt, Germany, in September 2003, high-level representatives of DaimlerChrysler, Honda and General Motors/ Opel have addressed the subject of fuel cell manufacturing costs. General Motors/ Opel has stated a manufacturing cost goal of \$50/kW for the entire fuel cell powertrain including electric drive motors for the market entry in 2010, and sees good chances to achieve this goal. DaimlerChrysler has confirmed that these manufacturing cost goals are achievable at production volumes of several 100,000 to one million cars. Also Honda has corroborated that these cost levels are achievable.

6.2 Fuel costs

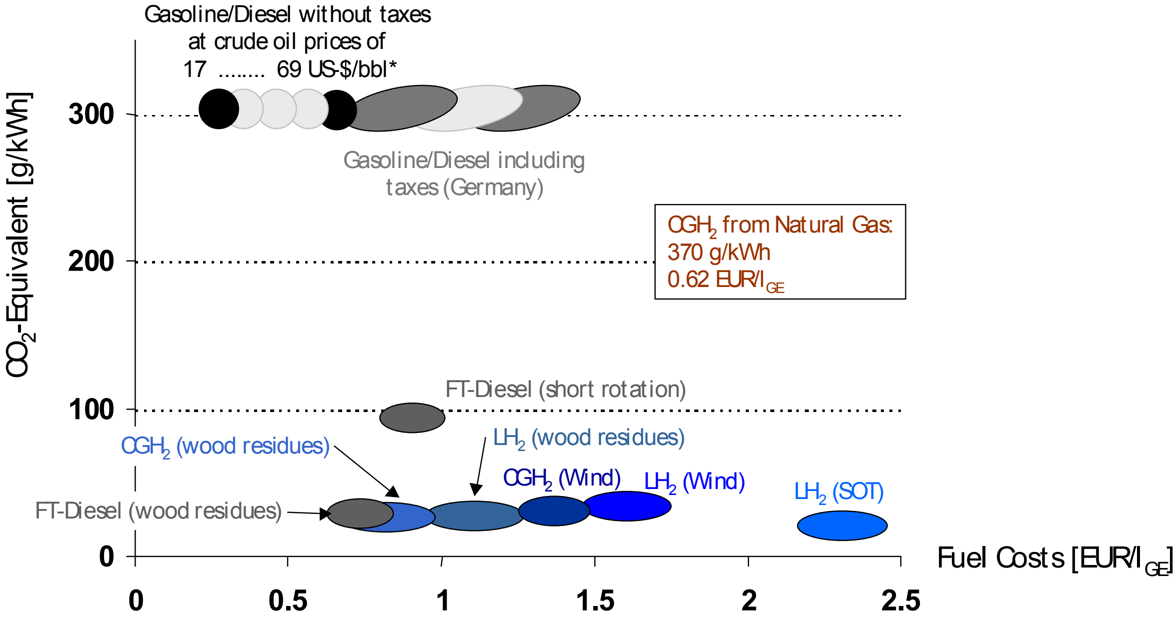
Hydrogen production and supply costs depend on various factors, the most important being the industrial context. At present, hydrogen is a chemical commodity, not a transport fuel. The industrial context of hydrogen fuel does not exist and consequently all cost projections have to be based on a future industrial scenario. Assuming niche markets for hydrogen only, production and supply costs will not be significantly different from today's high prices of this chemical commodity supplied by industrial gas companies to the various small industrial consumers.

In a scenario of large scale introduction of hydrogen as transport fuel, costs will be significantly lower than today for applications such as passenger cars, as the commercial and logistic structures will be entirely different. For other applications such as air or ship transport infrastructures will be similar to today's structures of captive hydrogen production and consumption. Very large amounts of hydrogen will be produced at the point of consumption. Today these are refineries or ammonia plants, in the future these may include airports and harbors.

Cost reductions in a scenario of large scale introduction of hydrogen as transport fuel will occur through economies of number and economies of scale. In decentralized hydrogen production paths, large numbers of identical components will be required (e.g. electrolysers, filling nozzles, flow meters etc.), which are technically available or which are being developed at present, but which are not series produced so far. Increasing market penetration will allow for larger installations (e.g. larger hydrogen filling stations for privately owned cars) inducing economies of scale.

The fuel cost estimates presented here are based on LBST analyses with the background of detailed assessments carried out in comprehensive Well-to-Wheel cost studies for automotive and energy industry. The estimates assume an industrial scenario of large-scale introduction of hydrogen fuel within the next 10 to 20 years. It has to be emphasized that cost projections depend on a number of assumptions making the results less reliable than projections of technical or environmental performance.

Figure 6-12: Fuel supply cost projection for 2010 versus greenhouse gas emissions per liter of gasoline equivalent.

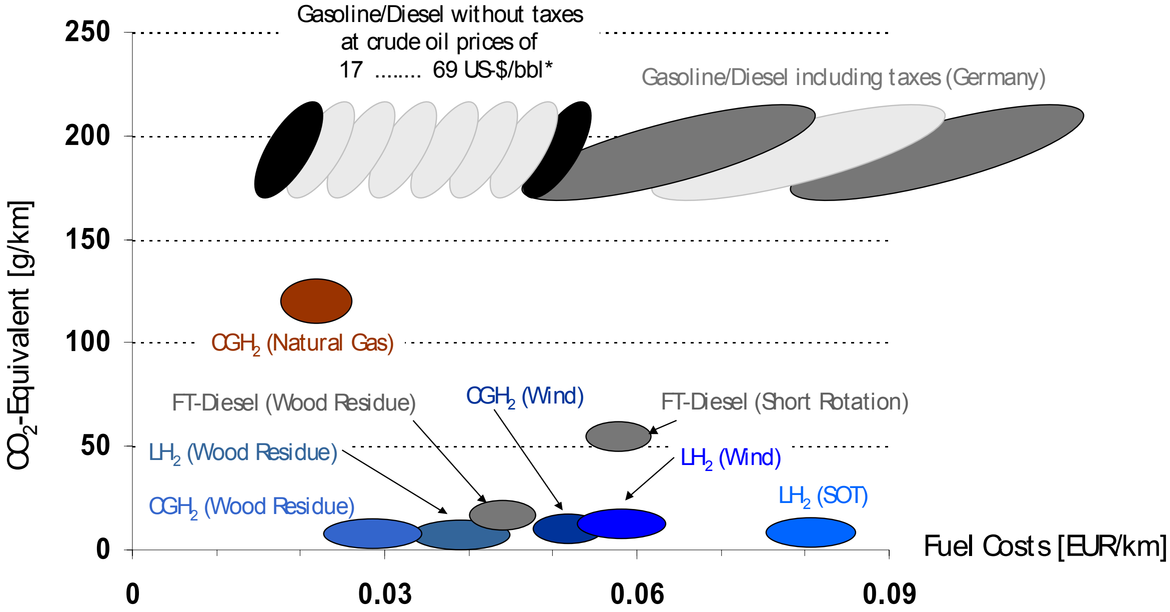


* 69 US-$/bbl was the annual average crude oil price of the year 1981 in real terms of 1995

Figure 6-12 shows the results of the analysis in terms of costs per unit of energy in a portfolio presentation together with the greenhouse gas emissions corresponding to each of the hydrogen production and supply paths. Numerical values are compiled in Table 6-2. Hydrogen fuel costs per unit of energy are not competitive with conventional fuels even at crude oil prices at the historic maximum of 69 US-$/bbl as the annual average price in 1981 in real terms of 1995. Hydrogen from natural gas or biomass can be cost competitive with fully taxed conventional fuel prices.

Because of the significantly higher fuel efficiency of hydrogen fuel cell cars, an economic comparison has to be based on costs per kilometer driven. Such a comparison is presented in Figure 6-13 (numerical values in Table 6-2). It is obvious that on this basis, hydrogen from natural gas and from biomass in a mass market comes close to full competitiveness with untaxed conventional fuel costs at current crude oil prices on the world market. Hydrogen from wind energy can come close to competitiveness at high crude oil prices. As discussed in chapter 7 “Evaluation of the potential for wide scale introduction of hydrogen as a fuel for each mode” geological shortages in crude oil supply foreseeable in the mid-term may lead to unprecedented high crude oil prices.

Figure 6-13: Fuel supply cost projection for 2010 versus greenhouse gas emissions per kilometer driven (Well-to-Wheel).



Gasoline: ICE (Otto cycle); CGH_2, LH_2: FC; Diesel, FT-Diesel: ICE (Diesel)
* 69 US-$/bbl was the annual average crude oil price of the year 1981 in real terms of 1995

At current oil prices, hydrogen fuel in a mass market can be made cost competitive by tax reductions similar to current tax reduction for natural gas as automotive fuel.

Qualitatively, the prices of fossil energies, especially oil and natural gas, are expected to rise, while the costs of renewable energies are decreasing due to continuing commercialization [WETO 2003]. Both developments are difficult to project precisely as they depend on many factors some of which are political choices. Nonetheless it is clear that the cost advantage of fossil energies will continue to decrease leading to an economic advantage of renewables at a given time in the future. Consequently, fossil hydrogen costs will increase while renewable hydrogen costs will decrease. At the same time, the costs of conventional fossil fuels will increase as well. This effect has to some extent been included in the cost estimates presented here projecting costs to the timeframe 2010-2020.

Further cost reductions in renewable energies will occur, and stronger price increases in fossil energies may take place, improving the competitiveness of renewable hydrogen.

This picture is qualitatively the same for all transport market segments. The price differentials between the conventional fossil fuels and fossil or renewable hydrogen are different for each market segment, though.

Table 6-2: Hydrogen cost projection for 2010 for fuel production and delivery to the car (Well-to-Tank) and for km driven (Well-to-Wheel) compared to conventional liquid and gaseous fuels

Fuel type	Fuel Cost [€/GJ]	Fuel Cost [€/km]	Remark
CGH_2 from natural gas			
Central	14 – 18	0.017	hydrogen driven in
incl. CO_2 sequestration	16 – 20	0.018 – 0.022	FCV (non-hybridized)
Onsite	19 – 22	0.026	
LH_2 from NG – central	24 – 26	0.027 – 0.029	
CGH_2 from coal	19 – 21	0.021 – 0.023	hydrogen driven in
incl. CO_2 sequestration	22 – 24	0.025 – 0.027	FCV (non-hybridized)
CGH_2 – from wood residue	22 – 28	0.023 – 0.035	H_2 driven in FCV
– from poplar plantation	29 – 37	0.033 – 0.042	
LH_2 – from wood residue	33 – 36	0.033 – 0.042	H_2 driven in FCV
– from poplar plantation	44 – 47	0.049 – 0.053	
CGH_2 from offshore wind	41 – 46	0.048 – 0.055	H_2 driven in FCV
LH_2 from offshore wind	49 – 55	0.053 – 0.063	H_2 driven in FCV
LH_2 from solar thermal power (North Africa)	approx. 66	0.074 – 0.086	H_2 driven in FCV
Fisher-Tropsch Diesel from			
– wood residue	21 – 25	0.040 – 0.048	FT-Diesel driven
– short rotation poplar	24 – 31	0.054 – 0.062	in Diesel ICE
Gasoline/ Diesel (crude oil)			Otto-cycle ICE re-
– untaxed	7 – 10	0.014 – 0.023	spectively
– taxed	21 – 31	0.046 – 0.081	Diesel ICE

FCV – fuel cell vehicle, ICE – internal combustion engine, FAME – fatty acid methyl ester

6.3 Ships and airplanes

Hydrogen fuel cost analyses for ships and airplanes are carried out in much the same way as for passenger cars. Nonetheless, there is a fundamental difference: hydrogen propulsion technologies are in general not significantly more efficient than the conventional technologies.

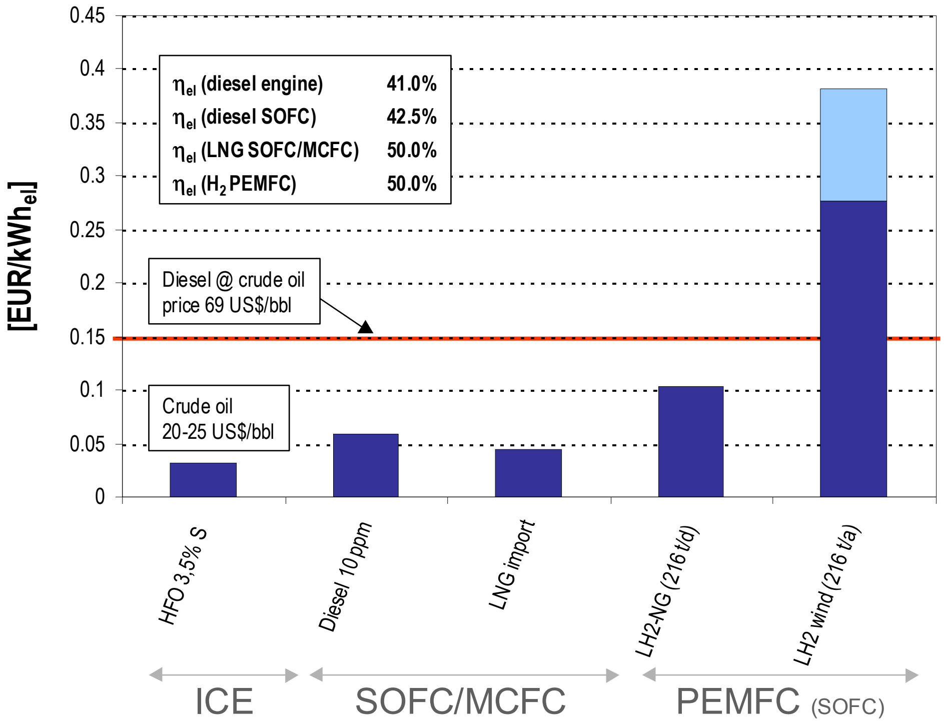
For ships this is due to the fact that large ship diesel engines achieve efficiencies of up to 50%, while high temperature fuel cells, possibly combined with gas turbines, still have to demonstrate theoretical efficiencies of 60% or even higher.

In large air planes, gas turbines are used for propulsion using kerosene today, and future concepts of hydrogen air planes include gas turbine propulsion using hydrogen.

Figure 6-14 shows the costs of ship propulsion or onboard electric power supply of 2 MW_e, corresponding to the greenhouse gas emission values presented in chapter 5.6.

While liquefied natural gas (LNG) is close to competitiveness with conventional heavy fuel oil, hydrogen from natural gas has higher production and supply costs. Hydrogen from wind energy is significantly higher in costs.

Figure 6-14: Costs of ship propulsion or onboard power supply of 2 MW_e.



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7 EVALUATION OF THE POTENTIAL FOR WIDE SCALE INTRODUCTION OF HYDROGEN AS A FUEL FOR EACH MODE

During recent years increasing numbers of detailed analyses have been published evidencing shortages of fossil resources in the foreseeable future. Most international experts agree that the maximum of world oil production will occur before 2020, some expect the maximum to be reached within the present decade. Rising energy prices will be the consequence accelerating the introduction of hydrogen fuel.

The technical potential of renewable energies in EU15 for the production of hydrogen fuel is higher than current and projected transport fuel consumption. There will be competition with stationary use of energy. Renewable energy potentials in regions close to Europe are huge.

All published scenario analyses for fuel cell vehicles agree that fuel cell vehicles offer advantages over conventional vehicles to the customer. If and as soon as this superiority can be realized at comparable costs, then fuel cell cars will very rapidly conquer very large shares of the car market.

Market introduction of fuel cell cars will take place in several phases: Until around 2010 a test and demonstration phase, until 2015 a market introduction and infrastructure build-up phase, and subsequently a market jump. In a pessimistic scenario, the first two phases take five more years delaying the market jump until 2020.

With market introduction starting in 2010, scenarios show market shares of up to 70% and fleet penetrations of up to 46% until 2030. Hydrogen fuel may replace up to 7% of conventional fuels in 2020 exponentially growing thereafter.

Combining these vehicle scenarios with assumptions on the production of hydrogen gives the overall greenhouse gas emissions of the passenger car fleet.

The downward trend of greenhouse gas emissions from conventional cars comes to a halt between 2015 and 2020 when all foreseeable technical advances have found their way into the car fleet. Further reductions are possible through the introduction of hybrid propulsion (reduced fuel consumption) and natural gas cars (lower carbon content of fuel).

Depending on the primary energy used for hydrogen production, significant greenhouse gas emission reductions may occur continuing the downward trend of greenhouse gas emissions from the car fleet after 2015-2020. Ultimately, emissions can go down to zero.

The availability of fossil energy resources and renewable energy potentials is discussed in the first section. These may potentially accelerate the introduction of hydrogen, or limit its production from renewable energy sources.

As the economic situation of the new accession states to the European Union is quite different from EU15 most of the analyses and estimates presented here refer to EU15. Analyses of the new accession states covering hydrogen and fuel cells are very scarce.

7.1 Energy Availability

The availability of primary energy resources for the production of transport fuels is a precondition for the supply of these fuels.

Traditionally, transport fuels are produced from crude oil in refineries. At present, first industry activities aim at producing conventional fuels from natural gas or biomass via Fischer-Tropsch synthesis. Coal may also be transformed into conventional fuels via gasification and Fischer-Tropsch synthesis.

Hydrogen can be produced from any primary energy source, including nuclear and renewable energies. In addition to the fossil and nuclear resources it is especially interesting to analyze the available potentials for renewable hydrogen production at European level.

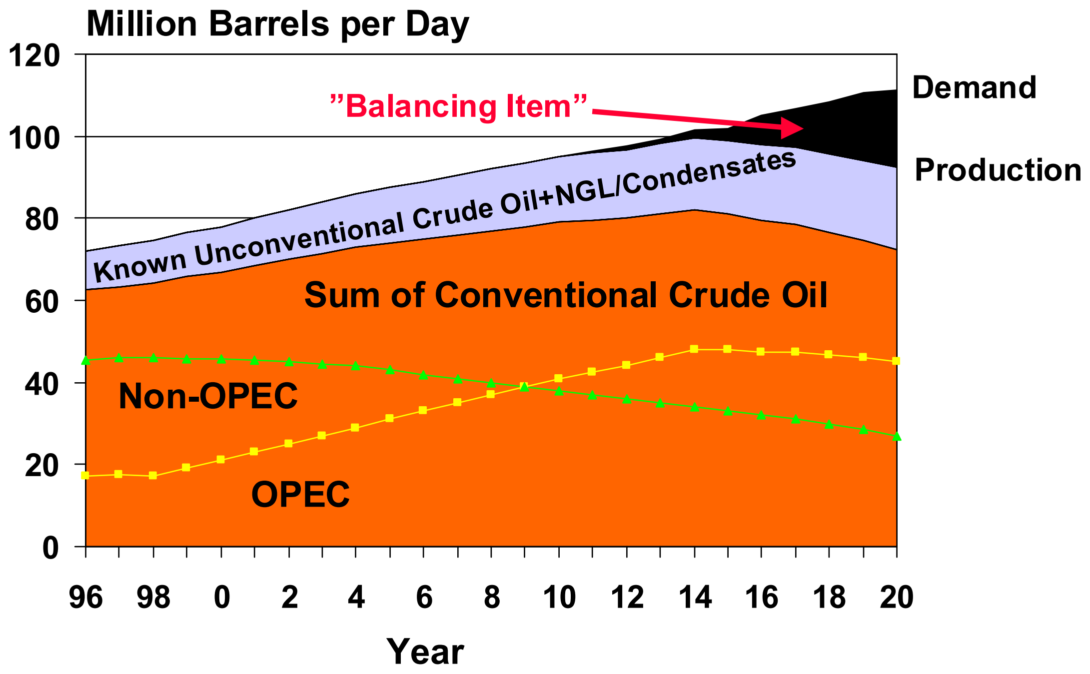
7.1.1 Fossil Resource Constraints

During recent years, the number of experts, especially geologists with a long experience in oil exploration, warning of constraints in the availability of fossil resources, petroleum in the first place, but also natural gas, is rising. Increasing numbers of detailed analyses have been published evidencing decreasing possible production rates of fossil resources in the foreseeable future.

The decisive criterion in this discussion on shortages of oil and natural gas supply is the quantity of oil/ gas supplied per year, i.e. the production rates, not the total amount of remaining resources. This is due to the fact that annual production levels are limited by geological constraints even if resources are still large. Once the production of oil and natural gas will have reached a maximum and begin to decline while world-wide demand continues to grow, prices will rise.

Most of the world-wide oil production basins such as the United States or the North Sea are very mature, i.e. their production rates are decreasing. In these basins, it is an empirical fact that production rates are independent of the remaining reserves. Official statistics in the USA still report increasing reserves while the production is decreasing since several decades. Only very few countries world-wide, mainly those located on the Arabian peninsula, might still be able to increase oil production. Hence, most of the international experts agree that the maximum of world oil production will occur before 2020, some expect the maximum to be reached within the present decade or even argue that it has been reached already. Figure 7-1 shows a projection of the International Energy Agency [IEA 1998] projecting the maximum of the oil production including known unconventional oil for the middle of the next decade. The difference between demand and production starting to open at the production peak is balanced by a “balancing item – unidentified unconventional oil”. [IEA 1998] projects the Middle East OPEC share of world oil production to increase from 24% in 1996 to around 50% until 2020.

Figure 7-1: World Energy Outlook 1998 oil production projections. Source: [IEA 1998]



The recent WETO study [WETO 2003] has modeled oil and natural gas price developments for the next 30 years. All results derived in the WETO study are based on this crucial parameter, which therefore should receive maximum attention.

Resources have been included in the medium and long-term price development by modeling the Reserves to Production Ratio with the reserves being determined in a Discovery Process Model within POLES. This methodology thus includes the principal finiteness of resources into the price model. Nonetheless, it does not include geological constraints in the possible production rates, which according to the geologists, is the decisive criterion limiting the availability of crude oil on the market in the foreseeable future.

Another point of concern is that the POLES model critically depends on reliable, detailed input data on the present reserves situation, and more importantly on the reserves yet to be discovered.

Figure 7-2: History and projections of petroleum discoveries world-wide. LBST analysis based on [USGS 2000], [IEA 2002], [Petroconsultants 1995], [IHS 2001]

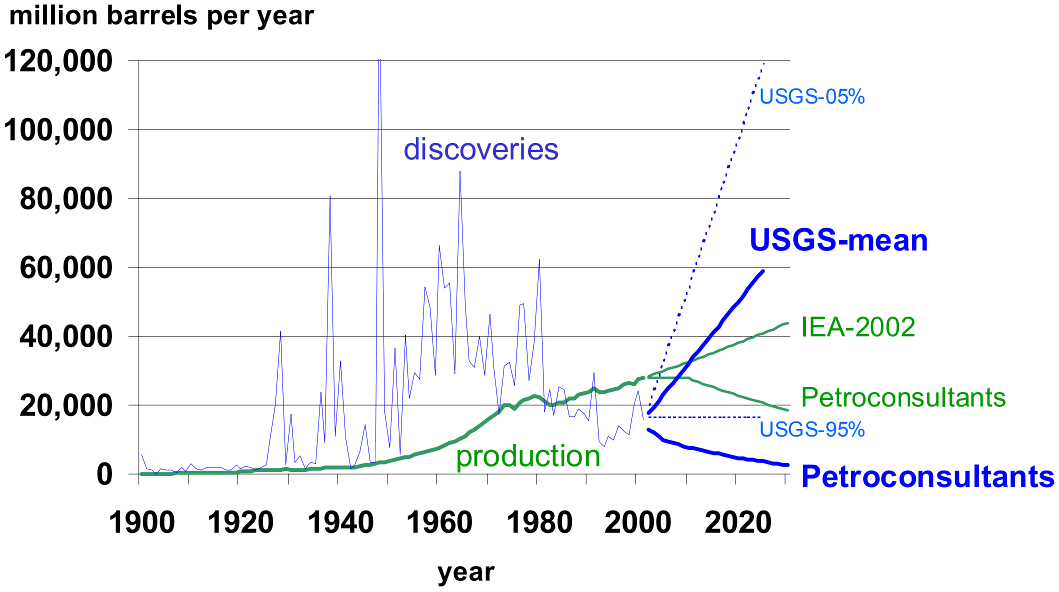


Figure 7-2 shows the discoveries of oil fields and oil production over the last 100 years as well as different future projections. The WETO study is based on the future oil discovery estimates presented in the latest study by the US Geological Survey [USGS 2000], which are denominated “USGS-mean” in Figure 7-2[1]. These values are by far the most optimistic values published during the last 20 years, representing a scenario which would more than reverse the declining oil discovery trend of the last 35 years with discoveries going down by some 3.5% per year. A detailed criticism of the methodology adopted and the results achieved in the [USGS 2000] study is presented in [Laherrere 2000]. The “low oil resources” case (denominated “USGS-95%” in Figure 7-2) discussed in the WETO study in order to assess uncertainties of the model may still be regarded as optimistic.

No scenario calculations based on a more pessimistic view of potential future discoveries of oil fields as presented by Petroconsultants [Petroconsultants 1995] or others have been carried out within WETO (see Figure 7-2).

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[1] [USGS 2000] has published total discoveries for the period until 2025 without assigning them to specific years. The assignment of single values to years is arbitrary. LBST has chosen a linearly increasing discovery trend for the presentation.

Figure 7-3: Historic and future oil and natural gas prices. Source [WETO 2003]

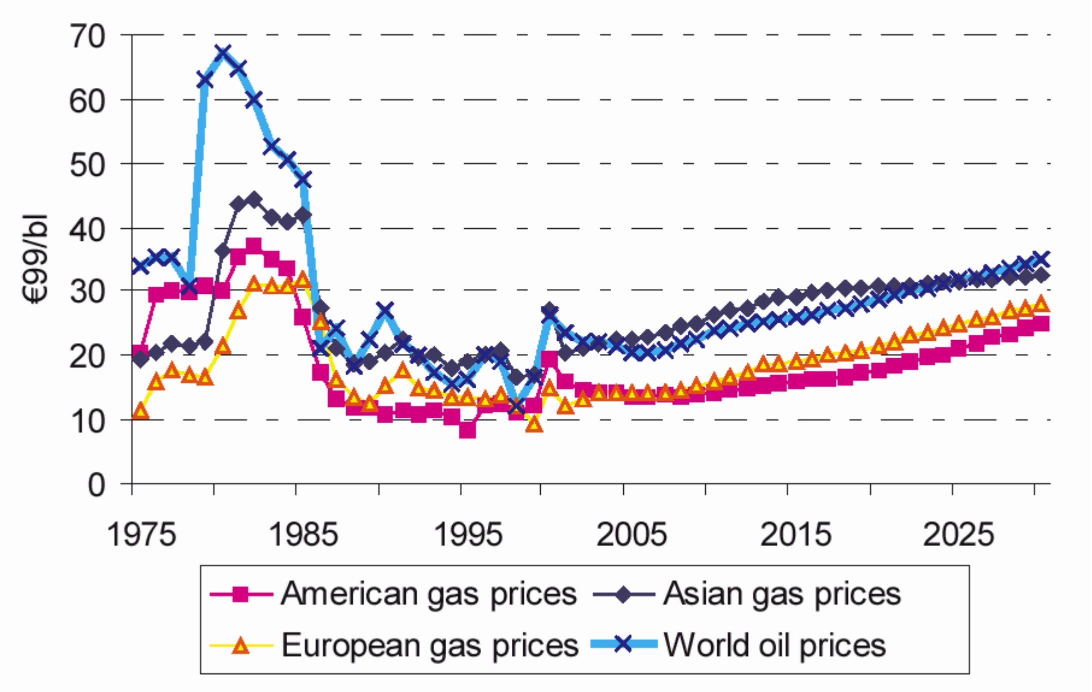

Figure 7-3 shows the historic oil and natural gas prices as well as the calculations of future prices from [WETO 2003] in real terms of 1999. The highest annual average oil price was recorded in 1981 at 69 Euro$_{1999}$ per barrel[2]. Analyzing the price volatility and price jumps during the past 25 years it appears unrealistic that oil prices will remain smooth and relatively low during the next 30 years.

7.1.2 Renewable Energy Potentials

Renewable energy potentials for the single production technologies have been analyzed in a number of studies. LBST has assessed these studies in detail in view of the renewable potentials for hydrogen generation in the European Union (EU15).

The goal of this analysis is to find out whether the availability of renewable energy sources for hydrogen production would be a limiting factor for the market introduction and subsequent penetration of hydrogen fuel cell vehicles.

Given the early stage of commercialization of renewable energy technologies, their presently small market share and the dynamic growth in this sector[3], LBST has made three

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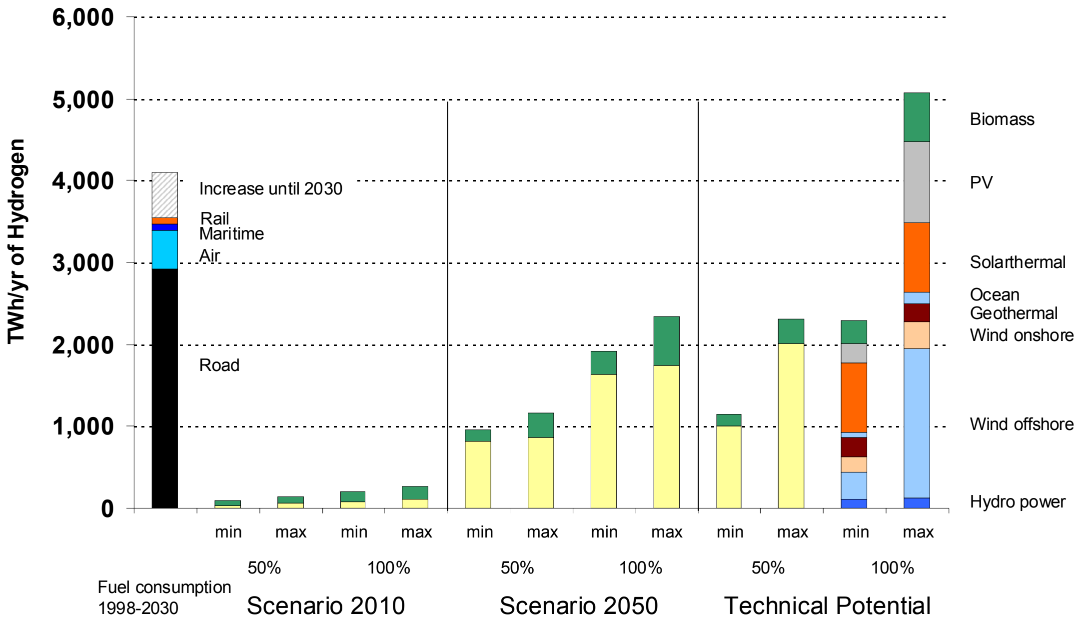
[2] Euro in real terms of 1999 is equivalent to US dollars in real terms of 1995.

[3] Hydro power, the only well-established renewable source of energy, is included in this analysis.

assessments: One estimates the amount of renewable hydrogen that could be made available by the year 2010 ("Scenario 2010"), the second is a very long-term (2020 to 2050) exploitation scenario based on a mixture of published scenarios, assessments and development goals ("Scenario 2050"), and the third estimates the very long-term total technical potential of hydrogen production within EU15 ("Technical Potential").

Figure 7-4: Renewable hydrogen production potentials in Europe; renewable electricity potentials have been summed in the yellow columns.



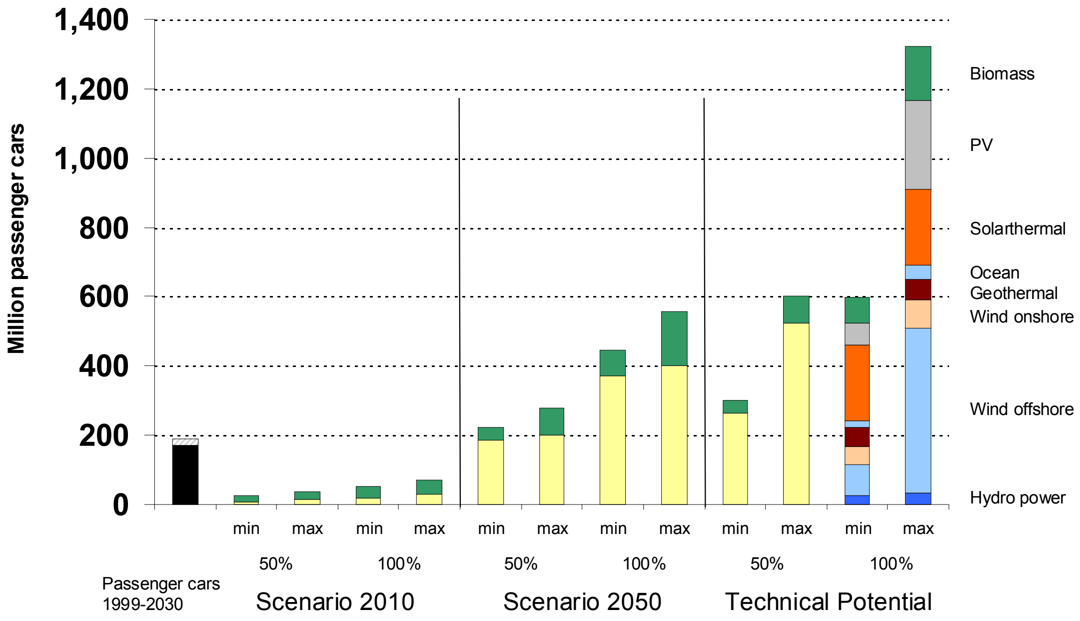
All values are subsequently translated into numbers of passenger cars by assuming an average fuel consumption.

The renewable energy potential estimates include electricity generating technologies (hydro power, wind power onshore and offshore, geothermal electricity, ocean energy [waves, currents], solarthermal electricity, photovoltaics on roofs and facades) as well as biomass (residues, dedicated plantation). The analysis is mainly based on [CECS 2000], [Ferrara 1999], [FfE 1998], [Kaltschmitt 2001], [LTI 1998].

The resulting values of the renewable energy potential in 2010 have to be regarded as an aggressive scenario that can realistically be achieved in case the necessary political choices are made. The estimates of the very long-term technical potential include environmental constraints, and they assume technical advances, especially in photovoltaics.

Assuming efficiencies for hydrogen production and supply for the different technologies, hydrogen production potentials are derived from the renewable potentials. Figure 7-4 shows these potentials assuming that 50% or 100%, respectively, of the renewable potentials are available for fuel production. Hydrogen potentials are compared to the EU15 fuel consumption in 1998[4] and to projections for 2030 based on [WETO 2003]. For the technical potential, the potential is broken down into the various renewable technologies, while for the other potentials the renewable electricity technologies are summarized in the yellow columns for better readability.

Figure 7-5: Number of hydrogen fuel cell passenger cars supported by the hydrogen fuel potentials



The number of hydrogen fuel cell cars supported in these scenarios is calculated assuming an average fuel consumption of 0.32 kWh/km (see Figure 7-5). This is about half the current average fuel consumption of the new passenger car fleet sold in the European Union, which reflects the 50% Tank-to-Wheel efficiency advantage of hydrogen fuel cell cars over conventional cars. It has to be emphasized that this assessment does not take into account light and heavy duty vehicles.

Electricity consumption in EU15 amounted to some 2,478 TWh in 2000. [WETO 2003] projects a growth to 3,841 TWh in 2030[5], or to 3495 TWh in the "CO_2 abatement case". Renewable

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[4] Maritime and air transport only include internal transport.

[5] In [WETO 2003], electricity production numbers are provided for "Western Europe", which is EU15 plus Iceland, Switzerland, Norway and Turkey. It is assumed here that growth within EU15 is the same as within "Western Europe".

electricity potentials amount to 119-189 TWh in Scenario 2010, to 2,372-2,557 TWh in Scenario 2050 and to 3,358-7,454 TWh as the Technical Potential (see Table 7-3 in the Appendix).

This analysis shows that sufficient quantities of renewable energies can be made available for hydrogen fuel cell vehicles, but that there will be a competition between fuel production and stationary application of the electricity, if electricity consumption grows as projected.

It should be noted that the potential for solar thermal electricity production in Northern Africa exceeds all renewable energy potentials in Europe, presenting sufficient potential for covering all energy requirements within the European Union through importation. Other importation routes are also conceivable. Thus, sufficient renewable energy potentials are available, either within EU15 or in its neighborhood, to supply renewable hydrogen to the road vehicle fleet in Europe.

7.2 Road transport

7.2.1 Market size

Table 7-1 presents major world markets for passenger cars and their respective sizes. Values for the timeframe 2010-2020 are based on rough LBST estimates and reflect the fact that these markets are essentially saturated [Dudenhöffer 2001]. The markets presented in Table 7-1 represent approximately 55% of the total world market in terms of car sales of around 56 million units per year [Dudenhöffer 2001].

[Dudenhöffer 2001] presents a market assessment of fuel cell cars including an analysis of the main factors influencing the market development. It is argued that not the entire world market is a potential market for fuel cell cars in the beginning. Until 2020, only environmentally sensitive regions and urban agglomerations in industrialized countries are seen as potential markets. The most prominent example is California with its zero emission policy, even though this has been revised several times.

The potential market for fuel cell cars is estimated at some 14 million passenger cars per year, which represents one quarter of the total world market. This potential market is broken down into the following three regions: US states with a high sensitivity to environmental issues (California, Connecticut, Florida, Maryland, Massachusetts, New Hampshire, New Jersey, New York and Washington) totaling 6 million car and light truck sales, urban agglomerations in northern and middle European countries[6] totaling 4 million car sales per year, and Japan with 4 million car sales per year.

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[6] [Dudenhöffer 2001] does not make explicit which countries these are.

Table 7-1: Passenger car market volumes [EU 2002], [US-CB 2002], [Dudenhöffer 2001]

Market	Registrations of new passenger vehicles (in millions)		Passenger vehicle fleet (in millions)	
	2000	2010-2020	2000	2010-2020
Europe (EU15)	14.3	16.0	177	200
Germany	3.8	4.0	42.8	50
USA	10.7 3) 4)	12.4	134 3)	155 3
California	1.4 3) 4)	1.5	17.3 3)	19 3)
Japan	4.0 1)	4.5	47 2)	56
Total	29.0	32.9	358	411

1) 1999 2) 1997/98 3) excluding personal passenger vans, passenger minivans and utility-type vehicles, which are included in the registration category "trucks" since 1990 4) calculated from total car fleet assuming an average lifetime of 12.5 years

7.2.2 Factors of success

Four factors determine the potential success of fuel cell vehicles in the market: Technology development, cost development, customer behavior and the political/ regulatory framework. These factors have been described in detail in chapter 4 "Technical, regulatory, economic, market and other obstacles and potential instruments to overcome them".

The essential point in all published scenario analyses for fuel cell vehicle introduction is that they agree that fuel cell vehicles offer advantages over conventional vehicles to the customer. If and as soon as this superiority can be realized at comparable costs, then "the winner takes it all", i.e. there will be no more reasons to buy conventional cars. Thus, fuel cell cars will then very rapidly conquer very large shares of the car market.

Customer advantages of fuel cell cars over conventional cars are:

- Increased efficiency, zero emissions.
- "All electric car" efficiently supplying quasi unlimited electric power for application in the vehicle or for consumption by external applications. This also facilitates the inclusion of driver support functions increasing the active and passive safety. Also, it facilitates or enables "x-by-wire" technologies.

- Superior torque and acceleration at low speeds increasing the “fun to drive” and the ride comfort.
- More flexible vehicle designs.
- Etc.

Societal advantages are mainly zero pollutant emissions, potentially zero greenhouse gas emissions (depending on the hydrogen production and supply path), flexibility in primary energy supply greatly increasing security of energy supply, and probably reduced noise levels.

7.2.2.1 Technology development, regulatory framework

For the subsequent analysis it is assumed that the remaining technical challenges especially in the area of fuel cell technology and hydrogen storage will be solved to a level allowing for mass production, as otherwise fuel cell vehicles will not be commercialized at all. It is further assumed that the regulatory obstacles will be removed as they also represent a killer criterion.

7.2.2.2 Cost development, political framework

Cost development refers to vehicle costs and fuel costs. Both are analyzed in detail in chapter 6 “Estimation of costs and future trends”. In a market introduction phase where production and sales volumes are still small compared to conventional vehicles, there is not necessarily a relation between manufacturing costs and sales prices. Best example is the Toyota Prius hybrid car, which has been introduced to the market in 1997 in Japan and in 2000 in the USA and Europe. The price had a slight premium over comparable cars, while the manufacturing costs at the beginning were estimated by experts as being double the sales price. To date some 140,000 Prius have been sold with drastic reductions in manufacturing costs through mass production in conventional production lines. The Prius represented 1.4% of Toyota car sales in fiscal year 2001. As soon as fuel cell vehicles represent significant shares of car sales of one manufacturer sales prices very much more have to reflect manufacturing costs. Thus, market introduction rates depend very much on company price policy. For the subsequent analysis it is assumed that fuel cell cars will have higher prices than gasoline cars. [Dudenhöffer 2001] assumes these price premia to be up to 20% in early market introduction. Cost goals communicated by industry on the other hand define maximum additional costs not exceeding common rail direct injection diesel engines, which translates to additional 1,500-2,000 Euro for a middle-class car.

Fuel costs are very much related to the political framework. Especially taxation is an effective instrument to support the introduction of hydrogen fuel. A reduced taxation level comparable to natural gas car fuel taxation in several European countries may be assumed for hydrogen. This may possibly have an element related to the greenhouse gas emissions of hydrogen supply and production. During early market introduction this may not be sufficient to achieve competitiveness. In a later stage of market introduction when hydrogen has reached several percent of overall transport fuel sales tax incentives should allow for competitive fuel prices (per kilometer driven) compared to conventional fuels and powertrains. Such a situation is similar to diesel cars in many countries where diesel fuel is cheaper than gasoline while the diesel car is more expensive to buy. Consequently, total cost of ownership is lower especially for people with a high annual driving range.

7.2.2.3 Customer behavior

Customer behavior is influenced by the total costs of car ownership including car price and fuel price (see above). In addition, factors of influence are the density of the filling station and the service network, the perception of fossil fuel resource constraints, uncertainties about performance in everyday use and about durability, uncertainty about whether fuel cells represent a dead-end or a major long-term development, the existence of political incentives as well as further psychological factors beyond the scope of the present analysis.

7.2.3 Phases of market introduction

Qualitatively, the market introduction and uptake of fuel cell cars may be subdivided into three phases building on “Phase 0: Feasibility and concept”, which has already been completed. Some probable qualitative characteristics of these phases are compiled below.

Phase 1: Tests and demonstration, characterized by

- First small series of fuel cell vehicles based on Phase 0 results and fulfilling all technical requirements.
- High image gain for vehicle manufacturers.
- High price premium compared to conventional vehicle.
- Uncertainty concerning performance in everyday use.
- Low density of the filling station and the service network.

Resulting in

→ Effectively no private demand for fuel cell vehicles.

→ Fleet applications, including public bus transport.

→ Improved vehicle designs.

→ Strategic company decision for the transition to Phase 2.

Phase 2: Market introduction and infrastructure build-up, characterized by

- Starting mass production of fuel cell vehicles.
- Initially thin filling station and service infrastructure rapidly growing to full area coverage (e.g. 20% of filling stations).
- Private customer market introduction starting in environmentally sensitive countries, mainly in urban agglomerations.
- Political incentives.

Resulting in

→ Growing customer confidence in the technology.

→ Growing private demand for fuel cell vehicles.

Phase 3: Market jump, characterized by

- Full mass production of fuel cell vehicles by all major vehicle manufacturers.
- Filling station and service infrastructure developing to 100% level.
- Market introduction in all world markets.

Resulting in

→ Exponentially growing market shares of fuel cell vehicles.

Most analyses (see 7.2.4 below) and communications published expect Phase 1 to last until around 2010, Phase 2 to last about 5 years, and Phase 3 to start around 2015.

7.2.4 Scenarios

Several scenario analyses for Germany, Europe or selected European markets have been carried out and published [Shell 1999], [Shell 2001], [Dudenhöffer 2001], others have remained unpublished. The development of a hydrogen roadmap for Germany has started. Within HyNet [HyNet 2003] goals and boundary conditions for a European Roadmap development will be defined until the end of 2003. The HyWays project, currently under contract negotiation with the European Commission, will develop a hydrogen roadmap for Europe based on the HyNet results.

Hydrogen roadmaps including scenarios or goals for hydrogen fuel market introduction have been defined and published for the USA, Canada and Japan. The Japanese car fleet penetration goals are to have 50,000 fuel cell cars in 2010, and 5 million cars in 2020, which corresponds to approximately 9% of the car fleet (see Figure 7-7).

Figure 7-6: Scenarios for the development of new hydrogen fuel cell vehicle sales.

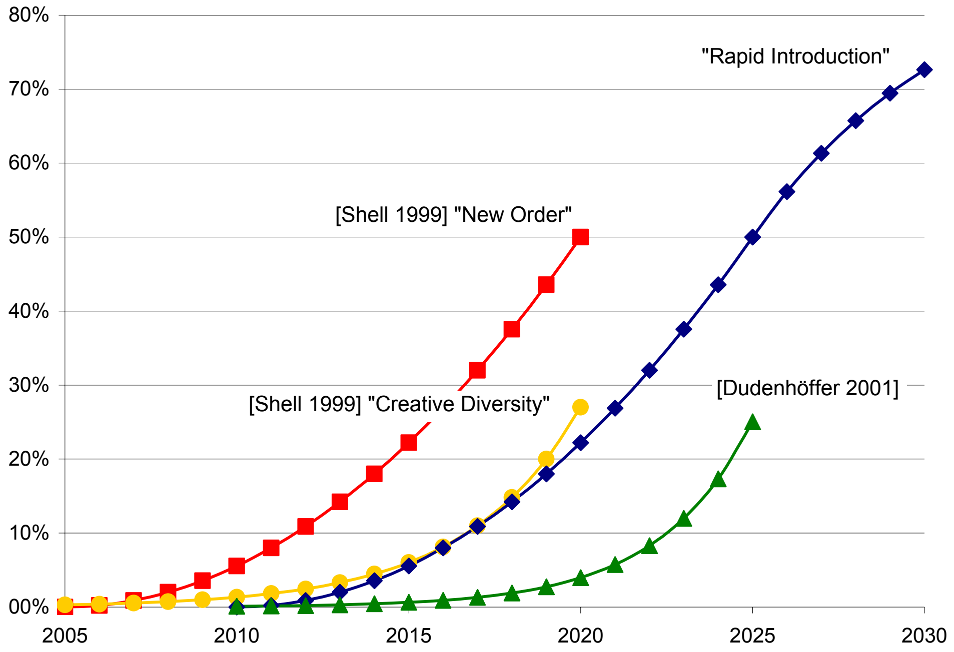
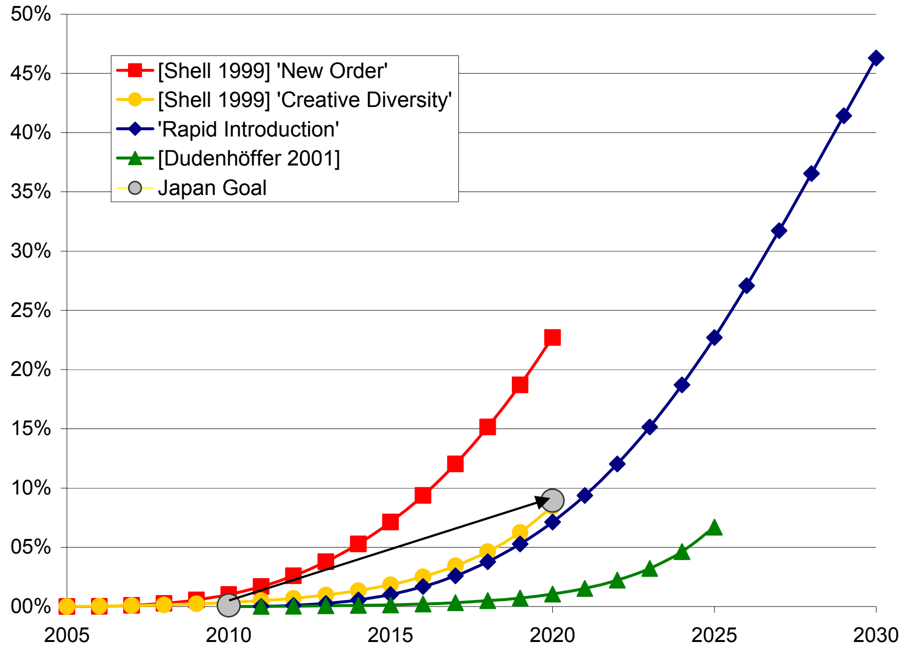


Figure 7-6 shows four scenarios of hydrogen fuel cell vehicles market share development, which may be regarded to span the range from aggressive to pessimistic. The two Shell scenarios are very similar to the “Rapid Introduction” and Dudenhöffer scenarios, respectively, with the difference that in 1999 Shell assumed market introduction to start in 2005. “Rapid Introduction” is an optimistic scenario following typical market development curves of innovations in the car sector. Figure 7-7 shows the fleet penetration of fuel cell vehicles corresponding to the vehicle sales presented in Figure 7-6.

Figure 7-7: Scenarios for the development of the fleet penetration of hydrogen fuel cell vehicles.

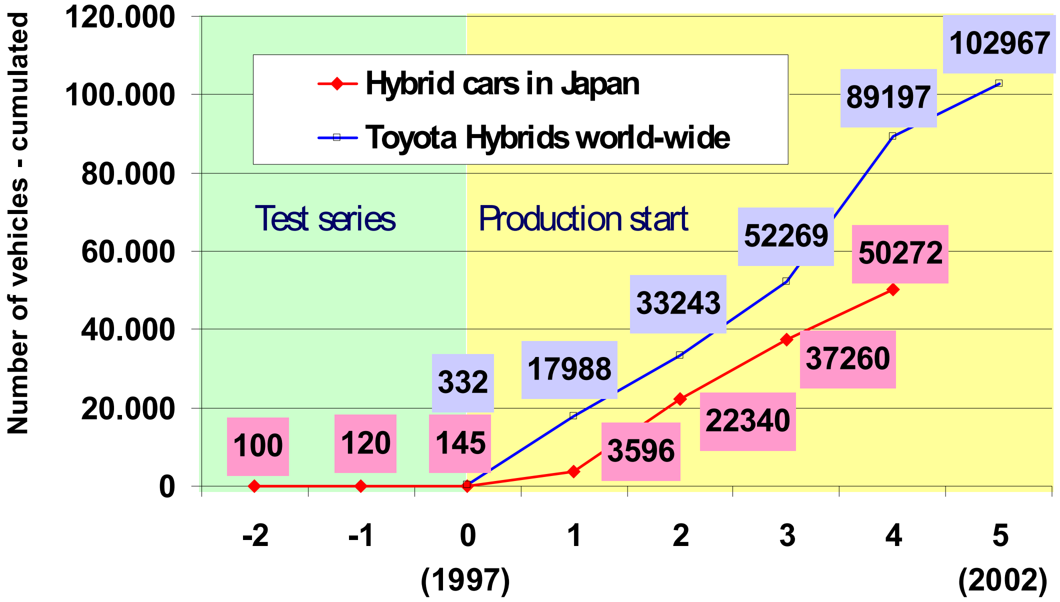


The Shell scenario "New Order" assumes that there will be a world-wide collaboration of automotive industry, and that the political framework will support the introduction of fuel cell vehicles. It is further assumed that the customers will accept fuel cell vehicles offering low noise, zero emissions and enhanced "fun to drive", even though they may be used in fleets and urban agglomerations in the beginning.

The Shell scenario "Creative Diversity" assumes that industry will not succeed in offering fuel cell vehicles for sale that have attractive economics and performance in everyday use in the beginning. After some 10 years, fuel cell vehicles leave their market niche through significant technology advances and start to enter the mass market. [Dudenhöffer 2001] assumes a similar reasoning for the slow market introduction in his scenario.

Those scenarios starting market introduction in 2010 show that in the long-term between 2020 and 2030 market shares of up to 70% and fleet penetrations of up to 46% may be achieved. In 2020, these scenarios include fleet penetrations of 1% to 7% with the same share of conventional fuels replaced by hydrogen, which has to be compared to the EU goal of 20% alternative fuels in 2020 [EU 2000] with indications in other EC communications that hydrogen might achieve 5%. On the other hand, the focus should rather be on the growth dynamics than on the exact values for a given year as all scenarios assume exponential growth with the "market jump" (phase 3; see 7.2.3) starting at the latest in 2020. In 2025, fleet penetrations and conventional fuel substitution are in the order of 7% to 23% already, growing to a maximum of 46% in 2030.

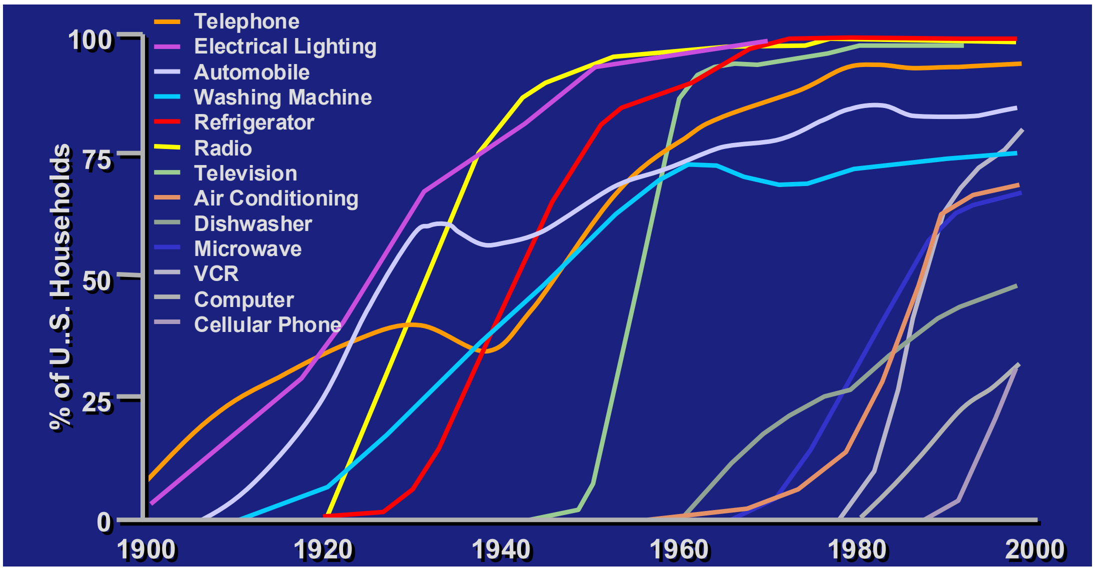
Figure 7-8: Market introduction of hybrid cars.



The analysis shows that a slow introduction of fuel cell cars will not happen. Either fuel cell cars will have a benefit for the customer and they will be offered for competitive prices, or there will be no commercialization at all. If and as soon as the technology will have been developed to a point where it achieves all performance goals at the manufacturing cost goals, then the market penetration will be very rapid. Figure 7-8 shows the market introduction development of hybrid cars, Figure 7-9 gives an overview of the market penetration of other technologies in the USA.

The leading automotive fuel cell developers are optimistic to achieve both the performance goals and the cost goals. The remaining question is when this will happen in which market. Indications are that 2010 will see the mass introduction of fuel cell cars in selected markets. This requires the entrepreneurial decision to be taken in 2005, and the technology freeze for the build-up of the manufacturing facilities in 2006.

Figure 7-9: Market penetration curves for various technologies in the United States of America.



7.2.4.1 Hydrogen consumption

A rough estimate shall be made here in order to give a quantitative appraisal of the hydrogen quantities required in the years 2020 to 2030 following the fleet penetration scenarios of hydrogen fuel cell vehicles as presented above.

Assuming an average hydrogen consumption of fuel cell cars on the road in 2020 of 0.3 kWh/km, which represents a 40% advantage over gasoline cars [LBST 2002], and an average annual driving distance of 12,000 km in combination with the assumed vehicle number from Table 7-1 gives the total hydrogen fuel consumption values of Table 7-2.

Table 7-2: Total hydrogen consumption of the car fleet in EU-15.

	Hydrogen fuel consumption [TWh/a]	
	“Rapid Introduction”	[Dudenhöffer 2001]
2020	51	8
2025	163	48
2030	333	

Present total hydrogen production and consumption in Western Europe (EU-15 plus Norway and Switzerland) is estimated at 180 TWh per year [CEH 2001]. Using the same assumptions, total conventional fuel consumption of passenger cars in EU-15 is roughly estimated at 1,200 TWh per year in case no alternative fuels are introduced.

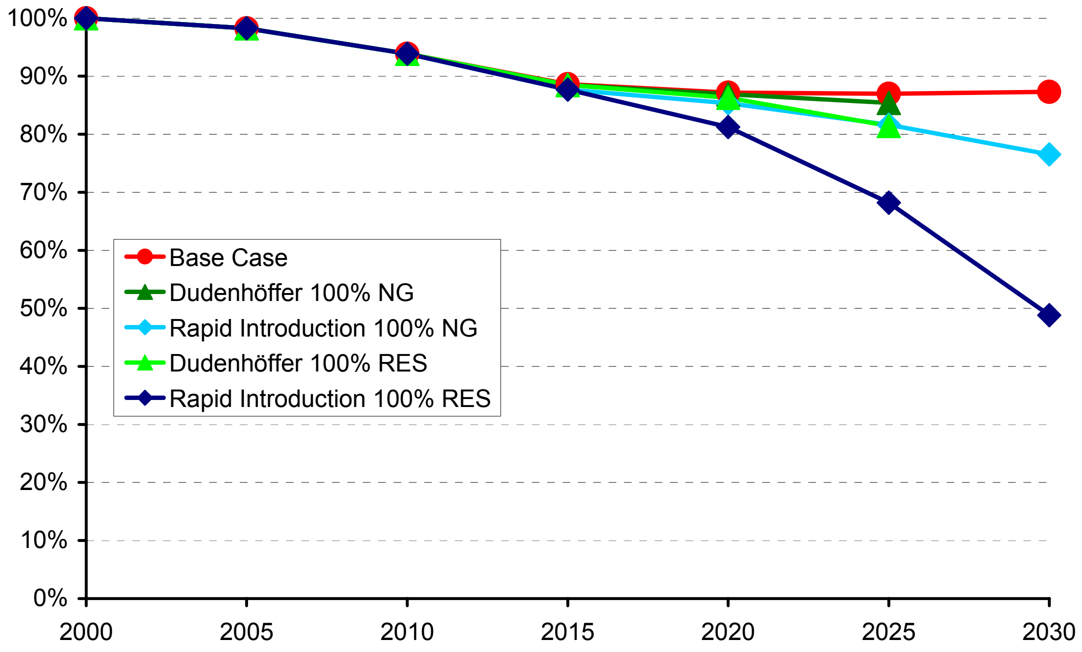
7.2.4.2 Greenhouse gas emissions

For the case of Germany the greenhouse gas emissions of passenger cars have been modeled [LBST 2002]. Assuming the fleet penetration scenarios presented above and extending the model to 2030 gives an idea of the potential contribution of hydrogen fuel cell cars to greenhouse gas emission reductions in the car sector (see Figure 7-10).

Fulfillment of the AECA self-commitment and a continuation of this downward trend in car fuel consumption until all technical fuel consumption reduction potentials will have been applied is assumed as the base case. A continued increase of total annual car kilometers traveled is assumed.

The downward trend of greenhouse gas emissions from conventional cars comes to a halt between 2015 and 2020 when all technical advances have found their way into the car fleet. Further reductions by around 10% seem realistic through the introduction of hybrid propulsion [GM-WTW 2002], maybe even more [MIT 2003]. The switch from gasoline/ diesel to natural gas as a car fuel would allow for additional reductions through the lower carbon content of natural gas. The total reductions depend on the fuel consumption and on the fleet penetration of natural gas cars.

Figure 7-10: Scenarios of greenhouse gas emissions from the passenger car fleet.



Depending on the primary energy used for hydrogen production, significant greenhouse gas emission reduction may become visible between 2020 and 2030. Assuming a pessimistic scenario for hydrogen fuel cell fleet penetration and hydrogen production from natural gas does not reveal significant emission reductions by 2025. Assuming an optimistic fleet penetration scenario, even natural gas derived hydrogen can bring about emission reductions of 15% and 24% until 2020 and 2030, respectively, compared to the year 2000 emissions, or an advantage of 2 and 11 percentage points, respectively, compared to the base case development. For renewable hydrogen, reduction values are 19% and 51% for 2020 and 2030, respectively, or 2 and 11 percentage points compared to the base case development.

7.3 Airplanes

Airplanes require a development time of 8 to 10 years. Hydrogen powered airplanes are presently under theoretical consideration, but no serious development efforts are being undertaken as far as publicly known. This means that hydrogen powered airplanes will not be commercially available before 2015.

Given these uncertainties and the long-term nature it does not make sense to develop market, fuel consumption and emission scenarios at present.

7.4 Ships

Fuel cells for the propulsion of ships are developed to a certain extent for military applications. For civil ships, there are essentially no developments so far. First considerations are being made in the FCSHIP project funded by the European Commission [FCSHIP 2003]. It is expected that fuel cell propulsion may become commercially available after 2015. For ships, not only hydrogen is a viable fuel for fuel cells, but potentially also other liquid or gaseous fuels.

In chapter 6 “Estimation of costs and future trends” and in chapter 5 “Life cycle analysis of the environmental impacts of the shift to hydrogen” some estimates of hydrogen costs and greenhouse gas emissions in ship fuel cell applications are presented. Greenhouse gas emission reductions require renewable hydrogen, while its costs are prohibitive at present energy prices. Fuel cells would allow for greatly reduced air pollutant emissions in ship propulsion. These rather general analyses have to be extended to specific ship types in order to identify potential early markets for fuel cells and hydrogen.

Given these uncertainties and the long-term nature it does not make sense to develop market, fuel consumption and emission scenarios at present.

7.5 Literature

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7.6 Appendix

Table 7-3: Renewable electricity potentials in EU15 in [TWh/yr]

	Situation 2001 Electricity production from installed renewable capacity	Scenario 2010 Renewable electricity from new capacity installed between 2001 and 2010	Scenario 2050 Renewable electricity from new capacity installed between 2001 and 2050	Technical Potential Additional potential not exploited until 2001
Hydropower	306	21.5	164	175-222
Wind offshore	0.3	14.7	514	551-3028
Wind onshore	32	67.0-133.2	238-333	333-541
Geothermal	4.5	11.5	367	368
Ocean Energy	0	0.4	125	125-250
Solarthermal	0	1.0	562	1404
Photovoltaic	0.2	2.8-6.9	402-492	402-1,642
Total Electricity	343	119-189	2,372-2,557	3,358-7,454

Table 7-4: Biomass and biogas available for production of hydrogen in 2010 [TWh/yr]

	Situation 2001 Biomass use in 2001	Scenario 2010 Additional biomass use in 2010	Scenario 2050 Additional biomass use in 2050	Technical Potential Additional potential not exploited until 2001
Lignocellulosic Biomass Residues	249	240	240-530	240-530
Dedicated Plantation	0	22-39	266-466	266-466
Biogas (organic waste)	29	29-43	125-224	125-224
Total Biomass	278	291-323	631-1220	631-1220

Table 7-5: Hydrogen fuel supply potentials and passenger cars supported

	Hydrogen fuel supply [TWh/yr]		Number of passenger cars [million]	
	50%	100%	50%	100%
Scenario 2010	102-137	203-274	26-36	53-72
Electricity	36-57	71-114	9-15	19-30
Biomass	66-80	132-160	17-21	34-42
Scenario 2050	854-1,067	1,707-2,134	222-278	445-556
Electricity	712-767	1,423-1,534	185-200	371-400
Biomass	142-300	284-600	37-78	74-156
Technical Potential	1,149-2,536	2,299-5,072	299-660	599-1,321
Electricity	1,007-2,236	2,015-4,472	262-582	525-1,165
Biomass	142-300	284-600	37-78	74-156

8 POLICY IMPLICATIONS

In addition to overcoming concrete obstacles and barriers (see chapter 4 "Obstacles and potential instruments"), the introduction of hydrogen as a transport fuel has a number of further policy implications.

Role of policy making

Policy making can direct industrial development and foster its international competitiveness in the areas of RD&D, of setting legal requirements, of setting suitable boundary conditions and of acting as a customer.

Public budgets are limited motivating the strive to maximize the efficiency and effectiveness of public spendings with regard to policy goals. In general, industrial budgets for RD&D are higher than public budgets, giving public RD&D spendings the specific role of financing basic research, of focusing on key areas with political priority, and of catalyzing specific developments. It is the role of industry to finance the major RD&D efforts in view of new business opportunities.

Setting legal requirements or contractually fixing industrial self-commitments is a means of limiting negative effects on environment, humans etc. At the same time, it may spur technological development and thereby increase the international competitiveness of industry.

Setting suitable boundary conditions, e.g. through specific taxation schemes or defining minimum or maximum market prices as in the renewable electricity or the telecommunications markets, policy making influences the profitability of certain products and services supporting or inhibiting market development in these areas.

Regulations, codes and standards fall into the latter two areas and are dealt with in chapter 4 "Obstacles and potential instruments".

Finally, policy making requires management and administration, which represents a non-negligible customer size on the market. This market power has the potential to support the market development of certain products and services. Military purchases also fall into this category.

Potential policy measures

A non-exhaustive number of potential policy measures are compiled and grouped in the three categories research, development & demonstration, legal requirements and market development in Table 8-1.

Each potential measure is assigned to one of the following general topics in Table 8-1:

- Increasing the efficiency of research funding.
- Increasing the competitiveness of European industry.
- Increasing the level of RD&D in hydrogen and fuel cells.
- Spurring technology development.
- Reducing greenhouse gas emissions from transport.
- Supporting market development of hydrogen fuel and fuel cell cars.

Table 8-1: Non-exhaustive overview of potential policy measures assigned to general policy topics.

	Increasing the efficiency of research funding	Increasing the competitiveness of European industry	Increasing the level of RD&D in hydrogen and fuel cells	Spurring technology development	Reducing greenhouse gas emissions from transport	Supporting market development of hydrogen fuel and fuel cell cars
Research, development and demonstration						
Definition of RD&D goals and topics in close cooperation with industry possibly supported by consultants and research	X					
Annual progress monitoring of funded projects and benchmarking of hydrogen and fuel cell technologies in Europe in comparison to the rest of the world	X	X				
Definition of a separate budget for hydrogen and fuel cell RD&D funding	X					
Budget increase for hydrogen and fuel cell RD&D funding			X			
Enlargement of European Commission capacities in hydrogen and fuel cells	X					
Increasing RD&D for military applications of hydrogen and fuel cells			X			
Legal requirements						
Setting of challenging legal requirements for the pollutant and greenhouse gas emissions of road vehicles		X		X		
Setting of progressive legal requirements for the renewable energy content of transport fuels		X			X	

	Increasing the efficiency of research funding	Increasing the competitiveness of European industry	Increasing the level of RD&D in hydrogen and fuel cells	Spurring technology development	Reducing greenhouse gas emissions from transport	Supporting market development of hydrogen fuel and fuel cell cars
Discussing a self-commitment of industry on progressive reductions of Well-to-Wheel greenhouse gas emissions as a continuation of the ACEA self-commitment		X			X	
Market development						
Commitment of the European Commission, national and regional governments to buy or lease hydrogen fuel cell cars in the test and demonstration phase as well as in the early market introduction phase						X
Define reduced tax rates for hydrogen fuel, optionally linked to the greenhouse gas emissions caused by hydrogen production and supply						X
Including transport in emission trading					X	
Military purchases of hydrogen fuel cell vehicles						X

8.1 Research, development and demonstration

8.1.1 Definition of RD&D goals and topics

Topic

Increasing the efficiency of research funding

Potential measure

Definition of RD&D goals and topics in close cooperation with industry possibly supported by consultants and research

Effects and consequences

- Industry developing hydrogen and fuel cell technologies with a view of commercializing products has a very good assessment of the R&D needs. Systematically including this knowledge into the political priorities could increase the efficiency of research funding in hydrogen and fuel cells. A combination of such a measure with progress monitoring and benchmarking (see 8.1.2) would increase the effect. Consultants and research could support the detailed specification of goals.

8.1.2 Progress monitoring and benchmarking

Topic

Increasing the efficiency of research funding and increasing the competitiveness of European industry

Potential measure

Annual progress monitoring of funded projects and benchmarking of hydrogen and fuel cell technologies in Europe in comparison to the rest of the world

Effects and consequences

- A public progress monitoring of funded projects on an annual level would make the RD&D progress in Europe transparent. It would give the European Commission as well as industry and research an easy method for verifying progress and the achievement of goals set out in the RD&D programs. In addition, it would support the European Commission in defining future RD&D goals.
- An annual benchmarking of hydrogen and fuel cell technologies in Europe in comparison to the rest of the world would support industry and research in the development of hydrogen and fuel cell technologies. It would give all players an efficient means of comparing their technologies to their competitors in Europe and overseas, and it would allow all players to have an overview of technology status and in fields related to their own technology.
- A first attempt of benchmarking has been started by the European Commission in the Energy Scientific & Technological Indicators and References (ESTIR) work [ESTIR 2002].

8.1.3 Separate budget for hydrogen and fuel cells

Topic

Increasing the efficiency of research funding

Potential measure

Definition of a separate budget for hydrogen and fuel cell RD&D funding

Effects and consequences

- A separate budget would give industry the confidence that a certain budget is definitely available, thus allowing a reasonable assessment of the probability of launching a successful proposal. This is an important aspect as the development of a project proposal requires a substantial financial effort.
- A separate budget would allow a comparison of future hydrogen and fuel cell funding between the USA, Japan and Europe.
- A separate budget would allow to define the political priority of hydrogen and fuel cells in Europe in a transparent way.

8.1.4 Budget increase for hydrogen and fuel cells

Topic

Increasing the level of RD&D in hydrogen and fuel cells

Potential measure

Budget increase for hydrogen and fuel cell RD&D funding.

In the USA funding levels of hydrogen and fuel cells in transportation including technology development for PEMFCs, hydrogen onboard storage, hydrogen production, supply and refueling infrastructure, fuel cell vehicle demonstration as well as regulations and standards work, reached US$76 million in 2002, US$97 million in 2003 and will reach US$165 million in 2004.The same areas of activity in Japan were funded at US$145 million in fiscal year 2003.

On the other side the total hydrogen and fuel cell funding of the European Commission, taking into account more areas and also stationary applications came to a total funding of 144.8 million Euro over five years in the Fifth Framework Programme. On a per year basis this is only 20% of any of the latest budgets in the US or in Japan, and even less when considering the broader scope of funding areas comprised. This difference of around 100 million Euro per year compared to any of the US or Japanese budgets was certainly not compensated by the total additional EU member state funding in hydrogen and fuel cells.

Public funding levels of hydrogen refueling station infrastructure in the Japan Hydrogen Fuel Cell demonstration project reaches 90%.

Effects and consequences

- An increase in the hydrogen and fuel cell RD&D budget on European level would increase the total level of RD&D activities in this field in Europe. The political support for hydrogen and fuel cells has increased significantly during the last year, which on the other hand is not reflected in the RD&D budget yet.
- An increased budget might allow Europe to catch up with Japanese and North American RD&D in hydrogen and fuel cells again.

8.1.5 Enlargement of European Commission capacities

Topic

Increasing the efficiency of research funding

Potential measure

Enlargement of European Commission capacities in hydrogen and fuel cells

Effects and consequences

- Increased capacities in the European Commission Directorates-General (Transport&Energy, Research, Environment and other relevant DGs such as Enterprise, Agriculture etc.) would allow for an increase of the internal competence on hydrogen and fuel cells and for the administration of increasing related activities.

8.1.6 Military research

Topic

Increasing the level of RD&D in hydrogen and fuel cells

Potential measure

Increasing RD&D for military applications of hydrogen and fuel cells

Effects and consequences

- RD&D contracts from the defense sector have been a major element of fuel cell development in North America and have enabled several start-up companies to develop fuel cell technology. Similar activities in Europe might have positive similar effects on the technology base and on the industrial structure of the sector, especially the support of SMEs.
- Military research contract allow for a 100% funding of R&D.

8.2 Legal requirements

8.2.1 Challenging emission regulations

Topic

Spurring technology development and increasing the competitiveness of European industry

Potential measure

Setting of challenging legal requirements for the pollutant and greenhouse gas emissions of road vehicles

Effects and consequences

- The definition of legally binding mid-term road vehicle emission goals for criteria pollutants and greenhouse gases on a Well-to-Wheel basis could spur important technical development. The California Zero Emission Vehicle Legislation has triggered the development of several new technologies to near commercial level, such as electric traction, fuel cells, storage and refueling of gaseous fuels etc.

8.2.2 RES goals for transport fuels

Topic

Reducing greenhouse gas emissions from transport and increasing the competitiveness of European industry

Potential measure

Setting of progressive legal requirements for the renewable energy content of transport fuels

Effects and consequences

- Legally requiring fuel producers to produce increasing shares of their fuels from renewable energy sources would open a large, growing market for renewable energies enhancing the competitiveness of the renewable energy industry. At the same time, the greenhouse gas emissions from transport would decrease accordingly.
- Such a requirement would not necessarily support hydrogen as there are other options of introducing renewable energies into fuel production, at least to a limited extent.
- Alternatively, this could be implemented as an industrial self-commitment (see also 8.2.3), or by emission trading (see 8.3.3).
- Such a measure could be limited to certain transport modes, or it could be implemented for all transport modes.

8.2.3 Industrial self commitment

Topic

Reducing greenhouse gas emissions from transport and increasing the competitiveness of European industry

Potential measure

Discussing a self-commitment of industry on progressive reductions of Well-to-Wheel greenhouse gas emissions as a continuation of the ACEA self-commitment

Effects and consequences

- A continuation of the ACEA self-commitment on the progressive reduction of greenhouse gas emissions from newly sold passenger cars beyond 2008, which would consider Well-to-Wheel aspects, would secure a mid- to long-term trend of decreasing greenhouse gas emissions from passenger cars. At the same time, it would allow the transport fuels industry to assume responsibility for the environmental effects caused by its products.
- Such a commitment would not necessarily support hydrogen as there are other options of reducing Well-to-Wheel greenhouse gas emissions, at least to a limited extent.
- Such a self-commitment on Well-to-Wheel basis would be an alternative to including the transport sector into emission trading (see 8.3.3).

8.3 Market development

8.3.1 Purchase commitment of EC, national and regional governments

Topic

Supporting market development of hydrogen fuel and fuel cell cars

Potential measure

Commitment of the European Commission, national and regional governments to buy or lease hydrogen fuel cell cars in the test and demonstration phase as well as in the early market introduction phase

Effects and consequences

- A commitment of European institutions and national and regional governments to buy or lease hydrogen fuel cell cars would provide an important early market for cars and fuel. The Alternative Fuel Vehicle Obligation in the USA may serve as an example requiring public fleet operators to purchase alternative fuel vehicles if the fleet exceeds a certain size. The problem of the obligation is that most alternative fuel vehicles run on both the alternative fuel and gasoline making it difficult to require the alternative fuel actually to be used. This problem exists for hydrogen internal combustion engine cars, but does not exist for hydrogen fuel cell cars.

8.3.2 Fuel tax incentives

Topic

Supporting the market introduction of hydrogen fuel

Potential measure

Define reduced tax rates for hydrogen fuel, optionally linked to the greenhouse gas emissions caused by hydrogen production and supply

Effects and consequences

- Tax reductions have shown to support the market introduction of natural gas as a vehicle fuel. Tax reductions would have similar effects for hydrogen fuel. Cost estimates (see chapter 6 “Estimation of costs and future trends”) show that after an initial market introduction hydrogen costs can go down to levels where tax reductions would be sufficient to make hydrogen cost competitive with conventional fuels (per kilometer driven). Such a situation is similar to diesel cars in many countries where diesel fuel is cheaper than gasoline while the diesel car is more expensive to buy. Consequently, total cost of ownership is lower especially for people with a high annual driving range.
- The natural gas case has also shown that tax reductions only have an effect if they are defined for a long timeframe.
- If tax reductions are linked to reduced greenhouse gas emissions in hydrogen production and supply (Well-to-Tank) this would give an incentive for low-carbon supply pathways.
- During early market introduction tax reductions alone may not be sufficient to achieve competitiveness. In a later stage of market introduction when hydrogen has reached several percent of overall transport fuel sales tax incentives should allow for competitive fuel prices. In order to compensate for related reductions in national income, tax for conventional fuels may be increased.
- It should be noted here that there are no taxes or levies on fuels for international aviation or maritime transport. Thus, tax incentives do not apply to these transport modes.

8.3.3 Emission trading in transport

Topic

Reducing greenhouse gas emissions in transport

Potential measure

Including transport in emission trading

Effects and consequences

- The trading scheme for greenhouse gas emissions presently being introduced on European level does include certain sectors. An extension of emission trading to the transport sector may be envisaged in a second step. Depending on the exact concept of including transport into emission trading this would give incentives for further increasing car efficiency and/ or for introducing renewable energies into the fuels.
- Emission trading in transport would not necessarily support hydrogen as there are other options of reducing Well-to-Wheel greenhouse gas emissions, at least to a limited extent.
- An industrial self-commitment for reducing Well-to-Wheel greenhouse gas emissions would be an alternative to emission trading (see 8.2.3).

8.3.4 Military purchases of fuel cell vehicles

Topic

Supporting market development of hydrogen fuel and fuel cell cars

Potential measure

Military purchases of hydrogen fuel cell vehicles

Effects and consequences

- The military are a large transport vehicle customer. Several aspects make hydrogen fuel cell vehicles especially interesting for military applications. This market segment may therefore accept higher vehicle prices in an early market introduction phase. This would provide an important early market for cars and fuel.
- The US Army seriously considers purchasing several 10,000 fuel cell vehicles and has co-operations with car industry and has awarded an additional development contract for a fuel vehicle to an SME (see also 8.1.6).
- Fuel cells have been developed for submarine propulsion in Germany. Fuel cell submarines are sold to navies world-wide.

8.4 Literature

[ESTIR 2002] www.cordis.lu/eesd/src/indicators.htm