Institute for Prospective Technological Studies

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

## - Executive Summary -

*Matthias Altmann*

*Patrick Schmidt*

*Reinhold Wurster*

*Martin Zerta*

*Dr. Werner Zittel*

*(Edited by Hector Hernandez)*

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# 0 EXECUTIVE SUMMARY

## 0.1 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.

## 0.2 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 onsite 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.

## 0.3 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".

## 0.4 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 obstacles and drivers are summarized in two tables including an assessment when solutions for the obstacles are required and when first positive effects may be expected for each of the drivers.

## 0.5 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.

## 0.6 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.

## 0.7 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.

## 0.8 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.

Each potential measure is assigned to one of the following general 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.