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HYDROGEN ENERGY NETWORK START-UP SCENARIO

S. Weingartner, H. Ellerbrock

Deutsche Aerospace AG,
Space Infrastructure
D-81663 Munich

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Abstract

Hydrogen is widely discussed as future fuel and energy storage medium either to replace conventional fuels for automobiles, aircrafts and ships or to avoid the necessity of bulky battery systems for electricity storage, especially in connection with solar power systems. These discussions however started already more than 25 years ago and up to now hydrogen has failed to achieve a major breakthrough towards wider application as energy storage medium in civil markets. The main reason is that other fuels are cheaper and very well implemented in our daily life.
A study has been performed at Deutsche Aerospace in order to evaluate the boundary conditions, either political or economical, which would give hydrogen the necessary push, i.e. advantage over conventional fuels. The main goal of this study was to identify critical influence factors and specific start-up scenarios which would allow an economical and practically realistic use of hydrogen as fuel and energy medium in certain niche markets outside the space industry.
Method and major results of this study are presented in detail in the paper. Certain niche markets could be identified, where with little initial governmental support, either by funding, tax laws or legislation, hydrogen can compete with conventional fuels. This however requires a scenario where a lot of small actions have to be taken by a high variety of institutions and industries which today are not interconnected with each other, i.e. it requires a new cooperative and proactive network between e.g. energy utilities, car industries, those who have a sound experience with hydrogen (space industry, chemical industry) and last but certaintly not least the government.
Based on the developed scenario precise recommendations are drawn as conclusions.

1. Introduction

Hydrogen in principle offers a wide range of applications. As energy storage medium it combines transportability, storability - in contrary to electrical energy - and high energy density (energy per weight) with environmentally cleanliness when burned with oxygen or air to water. The main reason why hydrogen today cannot compete with fossil fuels in most civil applications is the fact, that hydrogen is not a natural ressource. In contrary to fossil fuels, hydrogen has to be produced by consuming energy and therefore cannot be considered as an energy source. Only in very specific areas where fuel costs are of minor importance, hydrogen is used as energy medium today. The most spectacular example is space technology, where hydrogen has been used successfully as propellant since the early days of space transportation.
The attractiveness of hydrogen for wider application increases with decreasing availability of fossil fuels and an increasing awareness of the menacing consequences of unlimited fossil fuel burning. Hydrogen can replace fossil fuel derivatives like gasoline, kerosine etc. and can help to reduce environmental problems at least locally, e.g. in high polluted areas.
This paper discusses the question where and under what circumstances fossil fuel derivatives can be replaced by hydrogen economically today and how hydrogen compares to alternatives. The topic of this paper has to cover all the way of hydrogen from its generation to its final application.

1.1 Generation and Production of Hydrogen

Generally hydrogen can be produced by chemical, electro-chemical and thermo-chemical processes.

In many chemical processes hydrogen is generated as coproduct. The required energy usually originates from fossil fuels. Steam-reforming of carbon hydrides is the most common and industrially advanced process to produce hydrogen.
The Kverner method uses natural gas (CH_4) directly for hydrogen production by splitting carbon and hydrogen by heat energy. A certain amount of carbon is burned to deliver the required energy resulting in carbon dioxide emissions.
Beside the Kverner method there are other thermochemical processes, e.g the iron steam process. In these processes heat is used to separate hydrogen from hydrogen containing molecules, e.g. water. Due to the high costs, these thermo-chemical processes are not widely used for industrial hydrogen production. The direct use of thermal energy for industrial hydrogen generation would offer a number of advantages, because it would help to increase the overall efficiency and reduce energy costs of hydrogen production.

The electro-chemical separation of water is called electrolysis and requires about 50 kWh of electricity per kg hydrogen assuming an efficiency of 80%. The electrolysis itself is environmentally neutral however it is important to consider also the electrical power generation. For the hydrogen it doesn´t matter whether the electricity has been produced by renewable energy sources like solar or hydro power or from nuclear or conventional fossil fuel based processes. The environmental impact however is of course very sensitive to the energy mix of electrical pow-

er generation. It is certainly very clear that on a global scale it is not reasonable to replace fossil fuel derivatives by electrolytically produced hydrogen as long as we use large amounts of coal, oil and natural gas to generate electricity.
However, there are certain niches and regions where hydrogen can be produced by electrolysis from renewable energies or as a co-product of todays electricty generation and distribution without using extra primary energy. These niches are explained in detail in chapter 2.

1.2 Potential Applications of Hydrogen

From a pure technical point of view, hydrogen can be used as fuel for all kinds of mechanical and electrical transportation. The chemical energy stored in hydrogen can be converted to heat by burning it with oxygen or air to water. All kinds of heat and combustion engines can be driven with hydrogen.
Furthermore, hydrogen can be converted to electricity via fuel cells with efficiencies in the order of 70%.
The use of hydrogen is attractive if one or more of the following statements is true:

- high energy density per weight is important, e.g. rockets, aircrafts, vehicles
- clean exhaust gases are required, e.g. vehicles for urban traffic, in-door operation
- electrical energy has to be stored, e.g. in combination with wind or solar power plants
- (electrical) energy has to be transported over long distances and/or an electrical grid does not exist, e.g. remote energy consumers
- hydrogen is produced as co-product, e.g. chemical industry, raffineries

Fig. 1 gives an general overview on hydrogen production processes and potential applications.

This paper concentrates on the application of hydrogen for vehicles, especially with regard to reduce toxic emissions in high polluted areas. For this application hydrogen has to compete also with the battery-car alternative. A general comparison of hydrogen and battery vehicles with regard to volume and weight penalties is shown in Fig. 2, each including additional tank weight and volume.

2. Start-up Scenario

A start-up scenario has to fulfil the following criteria:

- it has to be based on state-of-the-art technology
- the complete system has to be competitive with alternatives after a short introductory phase with regard to costs, practicability, safety, environmental impact and public acceptance. This is not necessarily required for the subsystems and their alternatives.
- it has to have a consistent long term perspective.

These criteria in mind, the study at Dasa has been focussed on the niche production of hydrogen via electrolyzers and its application as fuel for automobiles. Consequently, the purpose of the study was to identify scenarios where the environmental advantages of hydrogen cars are important and possible disadvantages concerning economics or others can be reduced to a minimum.

2.1 Hydrogen Production

In order to establish an area-wide supply of hydrogen it is necessary to produce hydrogen locally. This can be done in an economic way by a new type of alcaline electroly-

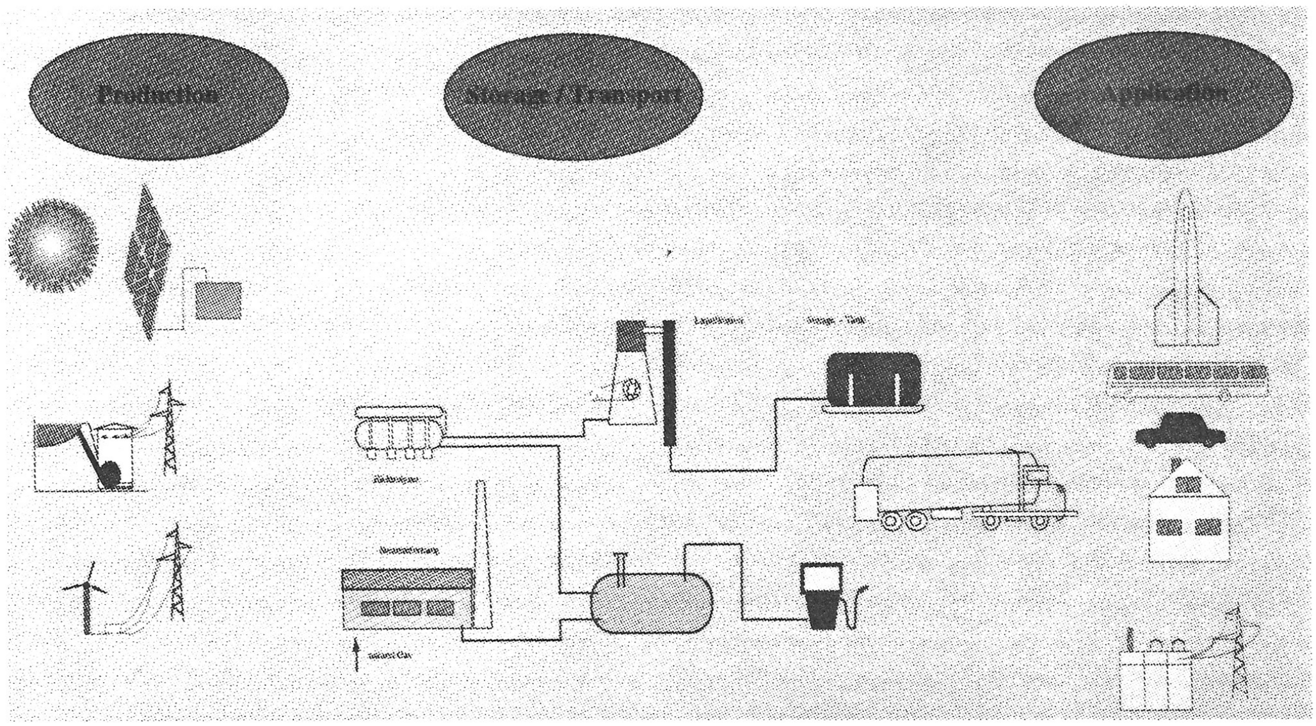


Figure 1: Hydrogen production processes and potential applications.

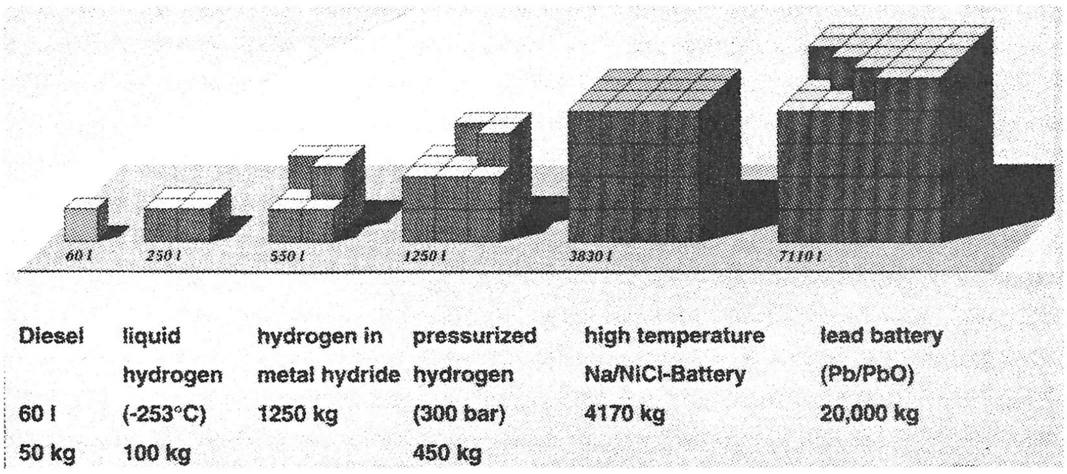


Figure 2: Comparison of diesel, hydrogen and battery energy densities for vehicle application /1/.

zer. The conceptual idea and a prototype electrolyzer are shown in Fig. 3.
Todays power plants continuously produce slightly more electricity than actually needed in order to maintain reserves when the demand increases. Furthermore, many power stations suffer from an efficiency reduction by being operated far off their nominal load point in order to adapt the electricity output to the actual demand.
Shortterm spinning reserves of power stations can be used efficiently and with little additional primary energy to produce hydrogen with an electrolyzer which has a wide range of operation and can be switched off whenever power reserves are needed for other consumers.
Such an electrolyzer has been developped by Dasa in a joint venture together with Linde AG, Munich and the Hamburgische Electricitäts-Werke, Hamburg, and it is currently tested in a prototype version with excellent results. The technical data of it is summarized in Tab. 1.

Tab. 1: Technical Data of 100 kW Electrolyzer /2/

nominal load:	100 kW
range of operation:	20 % to 120 % of nominal load
operating temperature:	150 °C (300 °F)
operating pressure:	> 30 bar (435 psi)
current density:	10 kA/m2
efficiency achieved:	> 82 % (at 10 kA/m2)
	> 87 % (at 5 kA/m2)
gas purity achieved:	
(at 20 % load)	H2: 99.8 %; O2: 99.0 %
(at 100 % load)	H2: 99.85 %; O2: 99.5 %

stack:	bipolar filter-press principle
operation:	intermittently operable
safety:	fully automatic operation, TÜV acceptance

Due to its high efficiency of about 80% a gallon gasoline equivalent of hydrogen could be produced for about 2.5 $ per gallon or 0.7 $ per liter gasoline equivalent. This value is not competitive with the gasoline price in the United States which is around 1 $ per gallon but can compete with the high taxed gasoline in Europe which costs about 3 to 4 $ per gallon or 0.8 to 1.1 $ per liter.

With the described concept an economic hydrogen infrastructure can be established, only depending on water and electricity.
The accessible reserves of power plants in Europe have been estimated to be in the order of 3 GW. This would allow a yearly production of 6 billions S m^3 of hydrogen corresponding energetically to 400 millions of gallons or 1.5 billions liter of gasoline which would be sufficient to operate 1 million passenger cars (10 l per 100 km and 15000 km a year). This amount is considered as being sufficient for a start-up scenario.

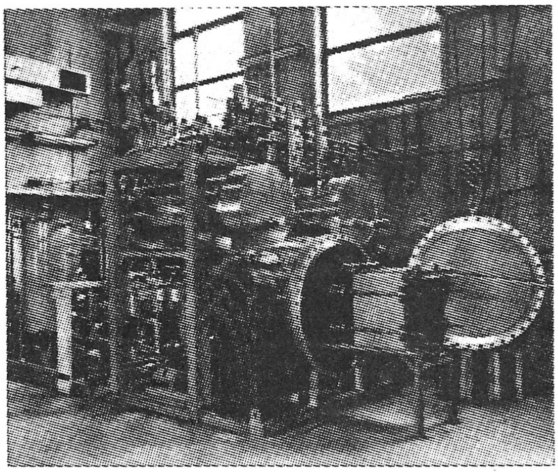
When further increasing the annual hydrogen production it is important to consider the energy mix of electricity production. In areas with little fossil fuel based electricity production hydrogen can help to reduce emissions and hence air pollution, at least locally. This especially is true for areas where main pollution is caused by traffic. A good example for such a situation is the Los Angeles basin.
With regard to the environmental impact renewable energy sources like hydro, solar, geothermal and wind power are attractive. But today only hydro power plants and in certain areas wind energy are competitive with regard to electricity costs.

For a mid-term hydrogen network the remaining hydro power ressources, especially in Norway and Canada could be used. In contrary to electricity, hydrogen could be transported to high populated areas in Europe or the U.S.
Solar energy based hydrogen production can be seen as a long term perspective. In very few, high insolated areas solar energy will be cost competitive in the near future.

2.2 Hydrogen Vehicles

2.2.1 Hydrogen Storage Options

For mobile applications hydrogen can be stored
- in its liquid phase at a temperature below 20 K
- as gas under high pressure of up to 300 bars
- in a metal hydride storage tank where the hydrogen is chemically bound to certain metals



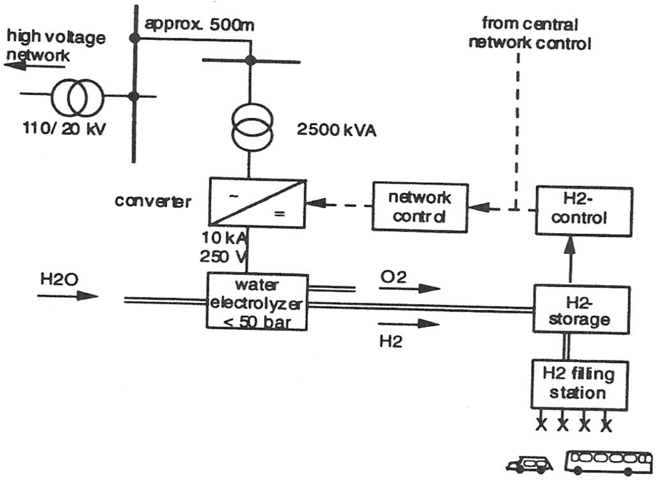


Figure 3: Hydrogen filling station with electrolyzer using spinning reserves of power plants.

Fig. 4 shows typical examples of these three storage options for automobiles.
Each option has its specific advantages and disadvantages which is illustrated in Fig. 5. For near term applications the metal hydride storage tank is the best solution because it combines high safety with low infrastructure requirements and hence low fuel costs. The low fuel costs result from the fact that there is no need to further pressurize or liquefy the hydrogen produced by the electrolyzer presented in chapter 2.1. Although tank weight and cost are disadvantageous features of the metal hydride option.

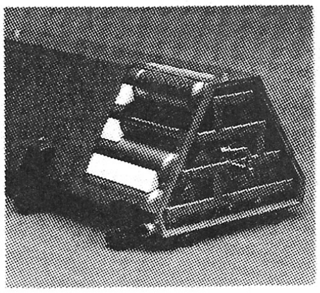
The energy densities of hydrogen, diesel and battery systems are compared in Fig. 2. Although liquid hydrogen has a three times higher energy density in kWh per kg, its low mass density (kg per m3) results in higher volume requirements to store the same amount of energy as compared to diesel. The weights given in Fig. 2 include additional tank weights (insulation, pressure vessel etc.).
Although it is difficult for hydrogen to compete with fossil derived fuels like diesel, it is very clear that hydrogen offers great advantages compared to battery systems which require huge volumes and unacceptable weights in order to store the energy content of 60 l diesel.

2.2.2 Cars with Hydrogen Combustion Engines
In order to minimize nitrogen oxide (NOx) emissions hydrogen engines should be operated at a mixture ratio of 2 (twice the air as needed for stoichiometric combustion). This results in a small reduction of efficiency and performance in the order of 15 % compared to gasoline engines.

The emissions of state-of-the art passenger cars are compared with hydrogen fueled and electric cars in Fig. 6 for the most relevant gases HC, CO and NOx. The small amounts of HC and CO emitted by hydrogen cars result from lubricant oil combustion /3/.
Zero emission can only be achieved by electric cars either with battery systems or fuel cells. Nevertheless, the emissions of hydrogen combustion engines are in the order of a few percent compared to todays passenger cars.
Furthermore, the range of battery cars gets unacceptable small if air conditioning, either heating or cooling, is required. Adding a fossil fuel burning heater will inevitably increase emissions well above those of a vehicle with a hydrogen combustion engine as illustrated in Fig. 6.

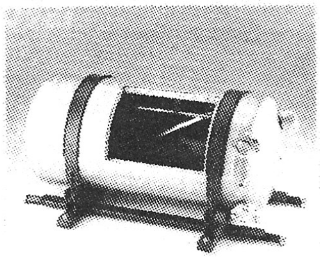
2.2.3 Cars with Hydrogen Fuel Cells
A fuel cell driven vehicle combines zero emissions and low noise levels with good performance and range. With an onboard reformer methanol could be used as primary fuel, transformed to hydrogen and then fed to the fuel cell, thus increasing range but causing low CO_2 emissions.
Europe´s first fuel cell car has been presented to the public by Daimler-Benz mid April 1994.
The fuel cell car has tremendous advantages, but today is far too expensive and can be seen as the long term solution only.
The battery vehicle has the mentioned disadvantages and becomes unpracticable for longer distances (more than 50 miles) or if air conditioning, either cooling or heating, is required.

2.2.4 Costs of Hydrogen Vehicles
The difference in operational costs of hydrogen vehicles compared to gasoline cars only depends on the fuel prices. Maintenance costs, insurance etc. are assumend to be comparable.
As stated before, hydrogen (to be filled into a metal hydride tank; req. pressure: 30 bars) can be produced for appr. 0.7 $ per liter gasoline equivalent which is, if no tax is added, competitive to the gasoline price in Europe. Pressurized (> 30 bars) or liquid hydrogen would cost 1 to 1.5 $ per liter gasoline equivalent.
The cost today for a hydrogen combustion engine vehicle would be in the order of 150 % of a standard car with comparable comfort. This extra cost could be reduced when increasing the number of produced hydrogen cars. A small extra charge on hydrogen cars will remain due to



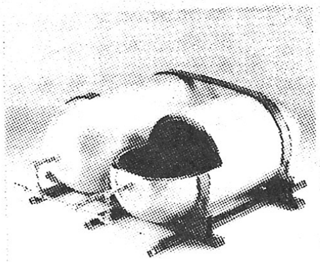
Metal-hydride storage tank

Weight: 320 kg / 705 lbs
Volume: 170 l / 45 gal
Pressure: 50 bar



Storage tank for liquid hydrogen

Weight: 20 kg / 44 lbs
Volume: 140 l / 37 gal
Pressure: 4 bar



Pressurized storage tank

Weight: 120 kg / 265 lbs
Volume: 250 l / 66 gal
Pressure: 300 bar

Figure 4: Hydrogen Storage Options for Vehicles

the more expensive storage tank. This extra charge is expected to be in the order of 10%, depending on the selected storage.
A comparison with battery cars shows that battery cars are far away from being competitive with hydrogen combustion vehicles /1/.
Fuel cell cars as well cannot compete with combustion engines today, but further cost reduction can be expected.

2.3 Attractive Niches

One major handicap of hydrogen cars is the non-existing infrastructure, i.e. there are no filling stations available today. This again is not a technical problem, but no gasoline station will offer hydrogen unless there is not a reasonable hydrogen demand (hen and egg problem).
It should be emphasized that cars with hydrogen combustion engines require the same infrastructure as fuel cell cars and therefore, the near term economic combustion engines could help to build up the infrastructure for the long term fuel cell option.

The following attractive niches have been identified:
- car fleets which require few central filling stations
- car fleets with moderate ranges and constant operating distances
- vehicles which have to operate in-door and out-door and need strong engines
- in areas where air pollution is critical, e.g. urban areas or air recreation ressorts

2.4 Supporting Boundary Conditions

The Zero Emission laws in California force car manufactures to sell at least 2% zero emission vehicles from 1998 and10 % from 2003 onwards. Similar laws are under discussion in other states of the U.S. Although it is not yet clear whether hydrogen combustion engines will be considered as zero emission, they would offer a good solution to establish an increasing amount of clean vehicles with comparable range, comfort and price as todays vehicles and also will decrease the entrance barrier for fuel cell vehicles (zero emission) by building up the required hydrogen infrastructure.
Also in Germany laws are under consideration in order to reduce traffic caused air pollution. This could result in a temporary closure of certain cities for conventional cars and therefore increasing the advantages of e.g. hydrogen vehicles which would still be allowed to enter the city.
Tax legislation could also be a method to improve the economic situation of clean fuels like hydrogen.

Another important support could be given by financing demonstration programs in which a complete system, including a filling station with an electrolyzer and a fleet of hydrogen cars is operated. Such programs are necessary to demonstrate the technical feasibility and safety and to gain public acceptance.

	complexity of infrastructure	H_2-cost gasoline equivalent $/l	$/gal	cost storage tank ($/kWh)	weight kg	lbs	range km	miles	safety	availability
liquid hydrogen	high	≥2,1	8	< 30	< 200	440	> 500	310	low	2005
pressurized hydrogen (300 - 400 bar)				< 60	< 500	1100				1998
metal-hydride	low	< 0,5	2	< 180	< 1200	2650	< 100	62	high	1993

= 60 l (16 gal) gasoline
for 100 kg (220 lbs) fuel and storage weight

Figure 5: Comparison of Storage Options.

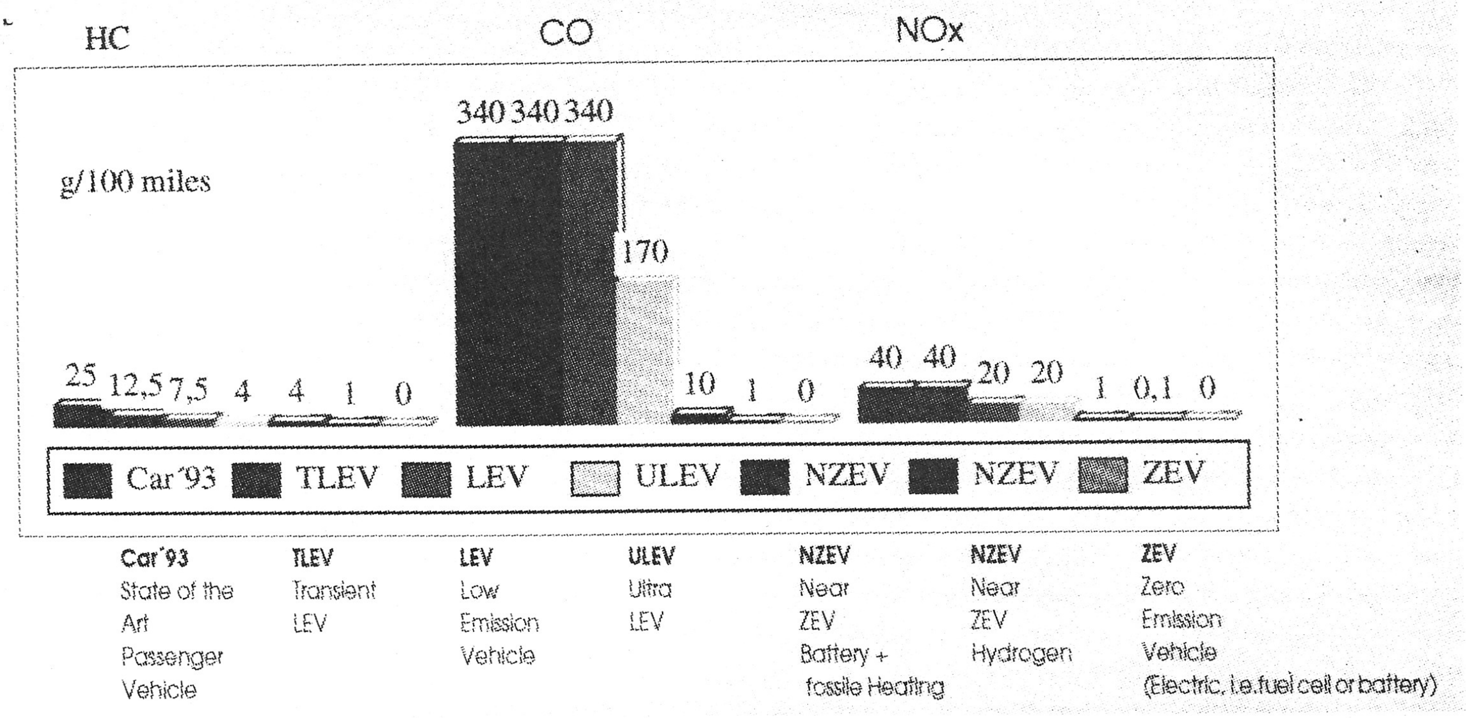


Figure 6: Passenger Vehicle Emissions in City Traffic

Best suited for such demonstration projects is public transport, either in large cities with air pollution problems or in health ressorts with clean air requirements.
In such cases the advantages of hydrogen can be demonstrated. A few filling stations would be sufficient and operational costs are comparable to those of conventional diesel vehicles

3. Conclusions and Recommendations

Vehicles with hydrogen combustion engines and metal hydride storage tanks are today technically feasible. Their cost could be reduced to 110 % of conventional cars when produced in higher quantities. Operational costs differ only due to different fuel costs. Hydrogen can be produced locally by electrolyzers for costs competitive with gasoline prices in Europe. The emissions of hydrogen combustion engines can be reduced to one percent of todays gasoline engines. Emission of fuel cell cars are zero but they are not cost competitive today. The long term perspective are fuel cell cars. They rely on the same infrastructure as hydrogen combustors.
Government can support the introduction of hydrogen as fuel by emission related laws, by taxes on polluting alternatives and by financially supporting demonstration programs, e.g. using hydrogen as fuel for public busses in high polluted areas. Demonstration projects are attractive where the environmental advantages of hydrogen are important and the required hydrogen infrastructure can be build up with a small number of filling stations. This starting infrastructure can later function as a nucleus of further mobile application of hydrogen.
All this requires a scenario where a lot of small actions have to be taken by a high variety of institutions and industries which today are not interconnected with each other, i.e. it requires a new cooperative and proactive network between e.g. energy utilities, car industries, those who have a sound experience with hydrogen (space industry, chemical industry) and last but certaintly not least, the government.

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