CHAPTER 1

FUTURE HYDROGEN USES FOR MOBILITY AND THE NEED FOR GREEN PRODUCTION ROUTES

Prof. Dr.-Ing. Horst E. Friedrich[1] and Simone Ehrenberger[1]

[1] German Aerospace Centre -DLR, Germany

ABSTRACT

In consideration of political targets for greenhouse gas emission reductions for the future, it is inevitable to look at how cars can contribute to CO_2 reductions in a sustainable way. A rethinking of vehicle technology is needed in the future. Hydrogen as alternative energy carrier provides several advantages when used for vehicle propulsion. The work presented aims at examining the use of hydrogen for mobility. We describe the role of hydrogen as alternative fuel, the most promising storage technologies and the environmental performance of hydrogen in comparison to other fuels. As the variety of vehicle concepts and energy carriers will increase, the examination of the whole production chains is necessary in order to evaluate the benefits of each technology. Fuel cells and hydrogen are a promising option on the way to a more sustainable transport.

1. INTRODUCTION

Facing climate change is a global challenge and has become a major political goal. The Copenhagen Accord presented at the United Nations Climate Change Conference 2009, although not ratified yet, agrees that global greenhouse gas emissions have to be cut down in order to inhibit an increase of the global temperature by more than 2°C. Transport emissions make up almost one quarter of total global CO_2

emissions. In consideration of enormous targets for greenhouse gas emission reductions for the future, it is inevitable to examine, how cars can contribute to CO_2 reductions in a sustainable and also economical way. The development of new vehicle technologies in combination with the use of alternative fuels is a major task for research. Hydrogen as alternative energy carrier provides several advantages, such as a possible environmental friendly production and a high degree of efficiency when used for vehicle propulsion. The work presented aims at examining the use of hydrogen for mobility. In the following, we first look at recent developments of alternative fuels before examining the use of hydrogen for vehicles. We focus on the most promising storage technologies and the environmental performance on hydrogen in comparison to other fuels.

2. FUTURE DEVELOPMENT OF FUELS AND DRIVE SYSTEMS FOR PASSENGER CARS

2.1. Hydrogen as Fuel

In the beginnings of automobile evolution, various fuels had been in use. Apart from mineral oil based fuels, ethanol and electricity had been discussed to be suitable for the new emerging technologies, but then fossil fuels have dominated the markets for decades. Today, as the world is facing climate change, possible scarcity of fossil resources and uncertainties in fuel supply, alternative fuels seem to promise the solution for these problems. The term "alternative fuels" includes substitutes for fossil fuels as well as fuels like electricity or hydrogen that can be used for new propulsion technologies (figure 1). Some energy carries, like electricity, can be produced from various primary energy carries. Additionally, some fuels, like hydrogen, can be used for various drive train technologies. Thus in the future, the variety of fuels and drive train technologies on the market is expected to grow.

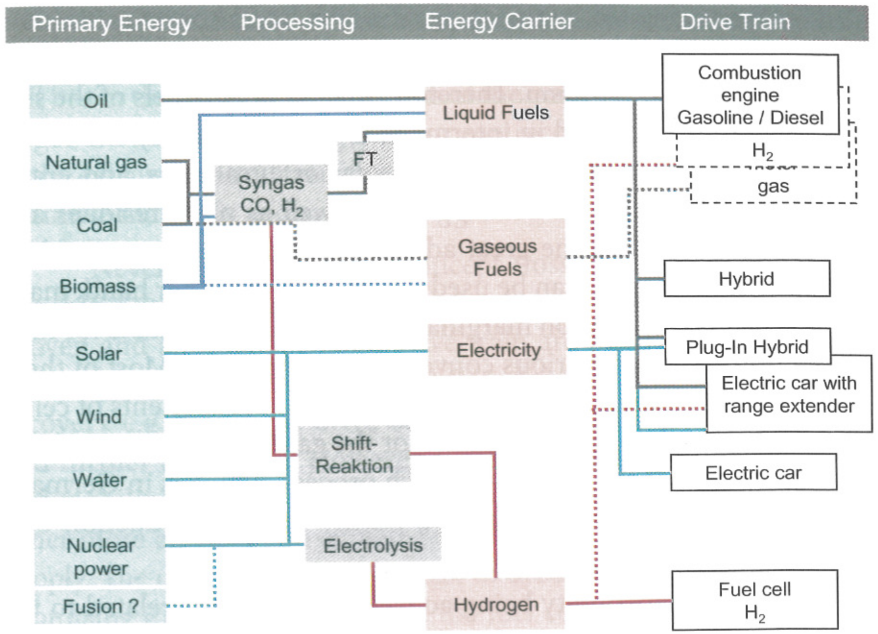

Figure 1: Overview of alternative fuel and vehicle technologies

Now and especially in the future, driving a vehicle has to be as environmentally friendly as possible. Regarding the reduction of greenhouse gas emissions, the use of fuels from biomass, the use of "green" electricity as well as the use of hydrogen from renewable sources is most favourable. Liquid fuels from biomass are the most common alternative fuels, as they can be used easily with conventional combustion engines. But their use is not per se beneficial from an environmental point of view. Critical aspects are, for instance, the increased usage of land and the environmental burdens arising from the application of fertilizers and pesticides associated with agricultural activities. In Brazil, for instance, new sugar cane plantings in the past few years lead to almost 2 million ha of new land cultivation [5]. Especially the elimination of primary rain forests, as massively happened for palm oil production in south-east Asia, must be seen critically. The destruction of valuable ecosystems cannot be evaluated by only considering greenhouse gas or energy balances.

Due to current competition of agricultural commodities and crops with the food supply, the production of fuels from biomass has recently come into criticism. Therefore, the use of bio-fuels of the second generation increased in intermediate term. Especially, the use of fast-growing woods such as willow, poplar or eucalyptus, and grasses such as miscanthus or switch grass, as well as plant residues and wastes are promising. The great advantage of these raw materials is that agricultural wastes can be used and that on the other hand, many of these plants can grow on marginal areas that are unsuitable for food production. There are various conversion technologies. Most of them are enzymatic techniques that convert the sugar components of cellulose and hemicelluloses into ethanol, or the gasification into synthetic gas. An example is the Fischer-Tropsch process, which is in Germany already operated commercially in a facility for the production of a synthetic diesel.

Another possibility being actively researched is related to the use of algae as raw material. Algae have the advantage of growing also in (semi) arid regions with poor soil quality or in salt water. The yield per algae hectare may be even greater than in tropical oil plants [1]. The primary nutrients for algae production are CO_2 and NO_x. Factory exhaust can possibly be used for feeding the stocks in the cultivation of algae. Different types of algae can be used depending on the fuel to be produced: bio ethanol, biodiesel or hydrogen.

Hydrogen, especially combined with fuel cells as energy converter, has been discussed for many years as a favourable fuel. In the long term, it promises to be produced with a high share of renewable energies.

2.2. Alternative Vehicle Technologies

Today's vehicle market is mainly based on conventional power trains with internal combustion engines and on the use of fuel made from crude oil and natural gas. On the way to increased energy efficiency in the drive train of passenger vehicles, first steps to improve the conventional internal combustion engines have been made. Tasks such as variable plug valve controlling and direct injection have already led to valuable improvements. Homogenization and variable

compression technologies which are related to emissions and fuel consumption reduction seem to be very promising. Additional potential still lies in the use of the energy loss of the combustion engine. For this target, the thermoelectric generator can recover some of the lost heat in the exhaust gas and transform it into electrical energy. The goal is to optimize materials and systems integration for up to 5% fuel savings.

Nevertheless, this drive concept "fossil fuel - ICE" is not sustainable without change. Two different ways of maintaining the proven and affordable engine-drive train are the use of CO_2-neutral bio-fuels as discussed in chapter 2.1, and the efficient energy use and recovery e.g. by hybrid drive concepts. They are already being used and further developed. However, further increases of traffic demand and mobility with only these measures will not be effective. There are other more efficient and climate friendly energy converters for power supply. The car of the future, at least in urban areas, drives electric. A promising drive concept is based the fuel cell which converts energy electrochemically. While currently dominated by the conventional internal combustion engine, future alternative propulsion technologies will play a major part in growing markets.

3. HYDROGEN INFRASTRUCTURE AND STORAGE IN VEHICLES

3.1. Hydrogen Infrastructure

Hydrogen is a high quality secondary energy carrier, not a primary fuel, and thus has to be produced from primary energy sources such as thermal or electric power. Energy for hydrogen production can be provided by various fossil as well as renewable feedstocks. Steam methane reforming is today's most important production route as it is the most economic process for large scale hydrogen production [2]. To meet the requirements of a sustainable production, a future hydrogen economy should, however, be based on alternative production routes.

Apart from the production of hydrogen itself, the transportation, storage and distribution of hydrogen is a key element for the development of an overall hydrogen system. The investment and operation costs for transport, storage and distribution of gaseous and liquid hydrogen in cost per unit hydrogen delivered have been analysed in various studies. In [6], a hydrogen pipeline network for the distribution of hydrogen to supply industry, households and road transport has been designed. Transportation, storage and dispensing of hydrogen imply technical and economic challenges. The costs for the hydrogen infrastructure depend on the dimensioning of the engineering solutions. The results show that the distribution of hydrogen adds to a significant amount to its production costs.

The most cost effective hydrogen transport option is the establishment of a pipeline network [2]. Generally, such a hydrogen infrastructure would be developed first in highly populated areas as this would be most cost efficient. Moreover, the environmental pressure for alternative energies is higher there. Considerable expansions of such pipeline networks in Europe are expected beyond 2040 for the hydrogen supply of cities in Europe, especially for household applications and small scale stationary fuel cells [2].

Considering the use of hydrogen for transport, the expansion of service stations connected by pipelines are linked to the introduction of hydrogen vehicles on the market. Depending on the introduction of hydrogen internal combustion engines and / or fuel cell vehicles, a comprehensive hydrogen infrastructure for transport is expected to be established in Europe not until 2030 [2]. Apart from pipelines, liquid or gaseous hydrogen can be delivered to service stations by tank lorries. Hydrogen road transport, however, is limited by the maximum allowed weight of the lorries and the time for loading and unloading the hydrogen.

The expected costs for hydrogen delivery range considerably in function of the type of infrastructure and customer (table 1). For industry supply, for instance, costs for hydrogen delivery by pipelines amount to 0.1 €/kg hydrogen, while for rural service stations, which are supposed to be served by road transport, costs add up to 1.1 €/kg. In cities, the delivery costs are lower (0.8 €/kg), when urban pipeline networks are used for the supply of service stations.

€/kg	urban service stations	rural service stations	urban households	rural households	industry
Trans-regional pipeline	0.09	0.09	0.09	0.09	0.09
High pressure pipeline	0.15		0.15		
Medium pressure ring	0.03		0.03		
Low pressure links			0.73		
Service station link	0.05				
Industry pipeline					0.01
Road transport (CH2)		0.63		0.63	
Service station	0.45	0.42			
Total €/kg	0.8	1.1	1.0	0.7	0.1
€/GJ	6.5	9.5	8.4	6.0	0.8

Figure 2: Costs for hydrogen delivery depending on infrastructure element and customer [2]

3.2. Hydrogen Storage Technologies for Vehicle Use

The fuel storage is the central component of the fuel supply chain. A major challenge for the use of hydrogen in vehicles is the low volumetric energy density of hydrogen and the resulting storage difficulties. Important features of the fuel system are the storage of the fuel, the fuelling system and connection to the energy converter. The most important requirements are:

- A high gravimetric energy density is required to keep the mass of the vehicle low.
- A high volumetric energy density is required to fit the fuel storage in the vehicle package properly. Furthermore, the fuel storage should be adjustable to the shape of the vehicle. Low self-discharge and leakage losses are required because of emission control and energy efficiency.
- Removal rates must meet the demand of the energy converter.
- For safety reasons, a high mechanical and thermal stability is necessary.

- Fuelling should be time and energy efficient. Additionally, it should be easy to handle for customers.

Figure 3 provides an overview of the storage options for hydrogen in vehicles. While vehicles with compressed gas or liquid storages are already available today, the most promising storage option is the use of metal hydrides. These three storage options are described in the following.

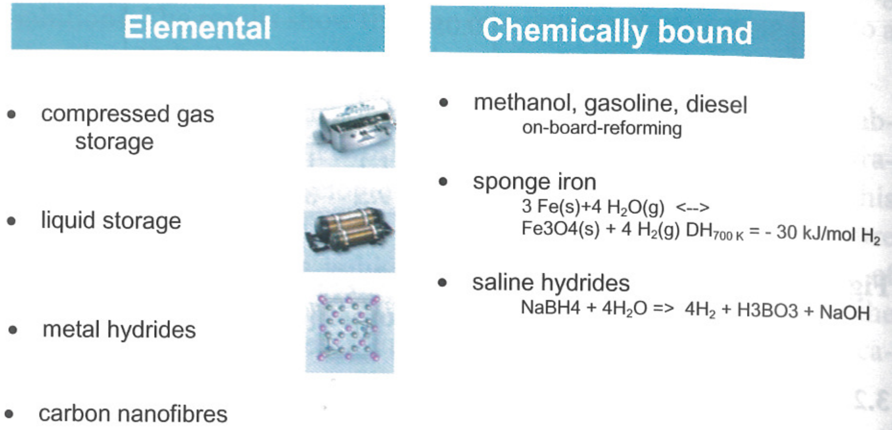

Figure 3:Options for hydrogen storage

3.2.1. *Compressed gas storage*

Perhaps the simplest way of storing hydrogen is as compressed gas in gas cylinders. Acceptable volumetric energy densities, however, can be reached only at very high pressures, because of the low density of hydrogen (figure 3). At a pressure of about 700 bar, a volumetric energy density of 4.8 MJ/l can be achieved. Compared to this, the energy density of diesel is about one order of magnitude higher. The energy consumption for fuelling at 700 bar is about 15 % of the chemical energy of hydrogen.

For automotive applications, the compressed gas storage is a comparatively cheap method. Hydrogen tanks have been tested in various car prototypes with pressures ranging from 35 to 70 MPa

[6]. In the past decade, technological developments for the optimization of these storages include the use of lightweight materials for the storage vessels having low permeation losses at the same time. Such tanks have showed high energy density at high pressures, while meeting European standard concerning storage safety. Today, a pressure of 700 bar is considered to represent a viable compromise between safety, volumetric energy density and energy consumption for fuelling.

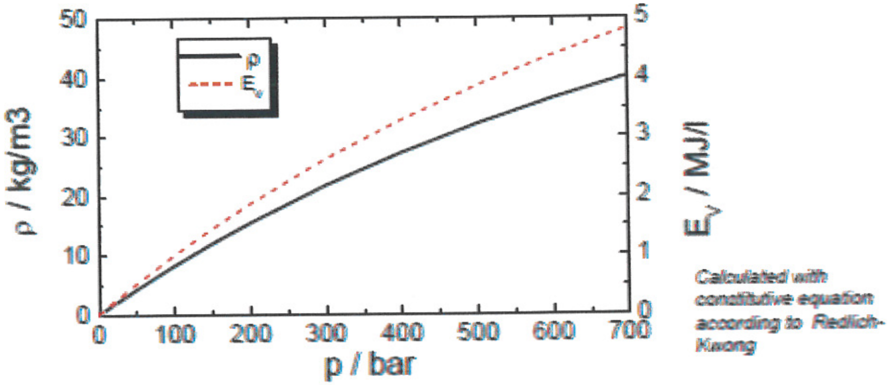

Figure 4:Correlation of storage volume and pressure for compressed gas storage

3.2.2. *Liquid storage*

Storing hydrogen in a liquid state leads to higher volumetric energy densities compared to compressed gas storage. Compared to a 700 bar gas tank, the volumetric energy density of a liquid hydrogen storage can be twice as high.

The essential properties of liquid-hydrogen storage are determined by the thermal and caloric characteristics of hydrogen. As hydrogen liquefies at 20.2 K (about -253°C) and 13 bar, the energy consumption for transforming the hydrogen gas into this state is high. Generally, the liquefaction process requires 30 % of the lower heating value of hydrogen [2]. Taking into account the efficiency losses for the overall energy supply chain (including production of electricity which is used in the process), the liquefaction of hydrogen requires more or less the same amount of energy which is stored in the liquid hydrogen.

For the use of liquid hydrogen in vehicles, hydrogen tanks have to show an extremely effective insulation and efficient refuelling technology. Such tanks can be made of cold resistant austenitic or alloy steels or non-metal materials, like composites. In order to avoid an increase of the pressure inside the vessel, they are generally designed as open systems [6]. Apart from optimizing the isolation features of liquid storage tanks, the adaption of the tank form to the designed space in passenger cars is a major challenge.

3.2.3. Metal hydride storage

Many metals and alloys have the property of being able to store hydrogen reversibly by reacting with it and forming a chemical compound which is commonly called metal hydride. The hydrogen is not stored elementary, but bound as protons in interstitial sites, whereas the outer electrons in an s-orbital passes into the electron gas of the metal. Metals with low electronegativity (A-ferrous metals) such as Mg, Li, La, Na, Ti and Cs, form very stable hydrides, while electronegative metals (B-metals) such as Fe, Ni, Cu and Cr are no or very unstable hydrides forms. Since only stable hydrides decompose at high temperatures and / or lower pressures, its technical application is difficult, especially in mobile applications. One approach to solve this problem is the alloy of metals with A-B-ferrous metals, leading to medium stable hydrides and therefore lower desorption temperature. However, this measure is associated with a decrease of the maximum load. For using the maximum loading of a stable metal hydride, such as magnesium hydride (MgH_2), high desorption temperatures are inevitable. Such materials have to be handled by appropriate technical measures such as optimizing the thermal management or improvements of the specific sorption behaviour by special manufacturing processes.

Table 2 shows examples for storage capacities for metal hydrides in vehicles. Depending on what alloy is used, the storage capacity and energy density vary considerably. Some materials achieve volumetric densities that are competitive to compressed gas storage.

The gravimetric energy density, however, is relatively low. Thus, the use of metal hydride storages in passenger cars would be beneficial particularly in terms of safety aspects.

Table 1: Metal hydride storage – vehicle examples [7]

Vehicle	System volume [l]	Alloy	System weight [kg]	Capacity [kg H2]	Energy density [MJ/kg]	Energy density [MJ/l]
MB310 Van	170	TiVMnTiF	568	6	1,492	4,988
Station Wagon	135	TiCrMnM	365	5	1,933	5,227
Forklift	130	LaNis	450	3,4	1,064	3,683
Minibus	550	FeMnTi	113	1,57	1,969	0,405
Jeep	250	FeMnTi	90	0,68	1,078	0,388
Pick-up	190	FeMnTi	433	5	1,629	3,713
Truck	144	FeTi	563	5,44	1,362	5,321

4. THE USE OF HYDROGEN FOR PASSENGER VEHICLES

4.1. Drive Train

The development of hydrogen-powered vehicles made a significant progress in the past ten years. Due to the search for alternative energy sources that would meet the world's rapidly increasing need for mobility, first hydrogen vehicles have reached a state which would allow an introduction on the market. Particularly in regard to the necessary infrastructure there are still problems to be handled (see chapter 3), while operational safety of hydrogen vehicles has made remarkable progress in the past years.

Hydrogen in the fuel cell is characterized by a high conversion rate compared to the combustion engine. In a tank-to-wheel analysis nearly zero emission vehicle concepts can be realized. However, hydrogen must be renewable and produced at low costs, in oder to achieve overall environmental benefits and to proof its profitability.

The fuel cell vehicle is in essence already an electric vehicle or an electric hybrid. Technological advancements have occurred for the basic component performance of fuel cell vehicles as well as for the overall system characteristics. Most promising fuel cell technology for vehicles is the so-called low-temperature proton exchange membrane fuel cell (PEFC) that can theoretically reach an energy conversion efficiency of 84% at room temperature related to the lower heating value of hydrogen.

Considering the vehicle architecture, future concepts are necessary which allow the use of different propulsion technologies on a basic vehicle platform. The approach of a modular drive concept designed at the Institute of Vehicle Concepts is presented in figure 5. One special feature of the concept is the scalability of the vehicle performance. The elements of different drive systems such as energy storage, energy conversion, etc. are designed modularly. Thus, they can be integrated in a basic vehicle platform. The modular platform is suitable, for instance, for the use of fuel cells or for a novel free piston linear generator as energy converter which has been developed at the Institute of Vehicle Concepts.

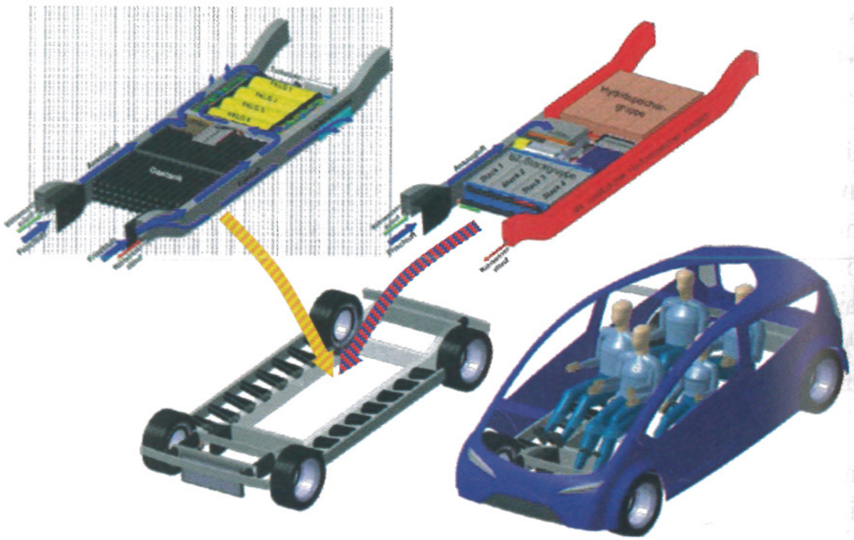

Figure 5:Modular drive concept by DLR

4.2. Energy and Greenhouse Gas Balance of Hydrogen

Further improvements of the vehicle efficiency with new technologies are essential to reach future CO_2 targets in the transport sector. This includes e.g. lightweight design of vehicles and the development of new alternative drive train technologies using batteries and fuel cells. The fuel market in general shows several alternatives such as different bio-fuels, natural gas and biogas that will penetrate the market at the same time. For good reasons, hydrogen and electricity might additionally enter the market. There are many challenges in the future in order to find the most economically and ecologically efficient solution.

For the calculation of greenhouse gas emissions not only direct emissions from vehicle operation have to be considered. For the evaluation of such environmental impacts, the overall supply chain has to be take into account. Figure 6 depicts the energy consumptions and greenhouse gas emissions for different fuels used in a middle class vehicle. The share of consumptions and emissions that originates from fuel production ("well to tank" (WTT)) compared to vehicle operation ("tank to wheel" (TTW)) differs considerably. For conventional fuels used in combustion engines, most of the greenhouse gas emissions stem from the vehicle operation itself. Electric or fuel cell vehicles are free from local emissions, but the production of the electricity or hydrogen which is required as fuels is linked to a certain amount of emissions. The shift of emissions from the use phase to the production phase is not per se beneficial. The state of the art production of hydrogen in the EU in 2007 shows higher greenhouse gas emissions than diesel or gasoline. Generally, for electricity and hydrogen, the reduction potential of emissions by using alternative productions paths is remarkable. In case of hydrogen, the production paths using renewable electricity or biomass are expected to be linked to low greenhouse gas emissions of less than 0.1 g per km.

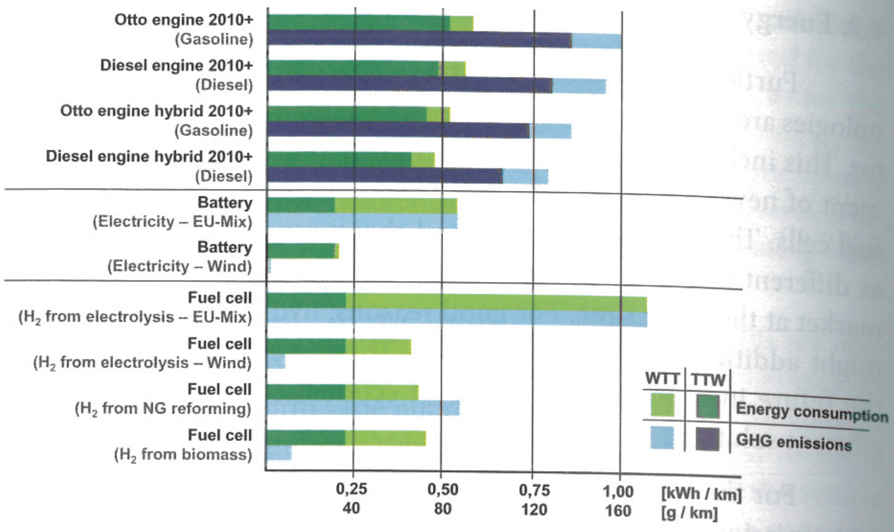

Figure 6: Well-to-wheel energy consumptions and greenhouse gas emissions for a Golf class vehicle [3], [4]

5. CHALLENGES AND PROSPECTS

The future development of market-ready alternative fuels and drive-trains for vehicles influences the environmental performance of the entire transport sector. Considering the global development of the automobile sector, there are three major trends for vehicle concepts:

- • High efficiency vehicles
- • Traffic optimised vehicles
- • Basic transportation cars

In Europe and North America, the automobile markets are characterized already by a large variety of different vehicle categories, which were optimized for their application. In addition to the conventional classification of vehicles such as limousine, van or SUV, a further classification of vehicles by their drive system has been

developed. Due to rising energy awareness, the internal combustion engine now competes with technologies that are based partly on it (e.g. hybrid vehicles) or can be characterized by a completely new architecture (such as fuel cells or electric cars). All advanced vehicle concepts, however, have common characteristics: from generation to generation they shift steadily to higher security, better driving performance and comfort.

Due to the increase in driving performance, especially in emerging economies, the need for energy efficient vehicles is growing in order to handle rising CO_2 emissions of the transport sector. Though for basic transportation cars the focus is on the general motorization of population, future developments for optimised vehicles will concentrate on the overall power consumption of the vehicles and the choice of energy sources.

Without significant improvements in vehicle and fuel technology, the emissions from passenger cars worldwide in 2050 are expected to be about twice the number of the year 2000 (figure 7). By implementing different CO_2 reduction measures, a reduction of such emissions from passenger cars of 40 % in 2050 compared to 2000 can be achieved. These measures include an introduction of new energy efficient technologies, the promotion of grid supplied electric vehicles and the creation of incentive systems to encourage energy and CO_2 savings. If such sustainability measures are not taken, the increase of CO_2 emissions by cars would be 110% [1].

Considering these challenges of climate change and the trends in mobility, rethinking of vehicle technology is needed in the future. Depending on different influencing variables or boundary conditions in fuel prices, CO_2 taxes or penalties, various scenarios are possible [8]. As the variety of vehicle concepts and energy carriers will increase, the examination of the whole production chains is necessary in order to evaluate the benefits of each technology. Fuel cells and hydrogen will be a promising option on the way to a more sustainable transport.

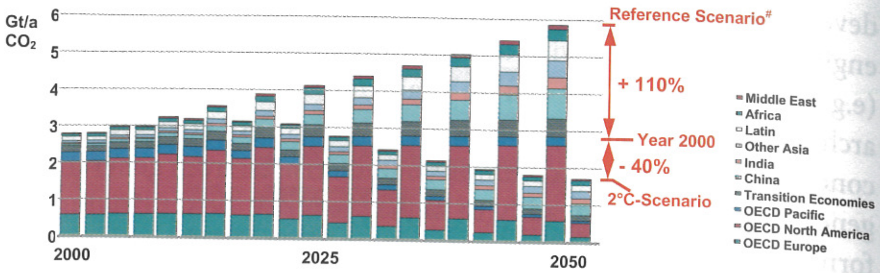

Figure 7:Prospected CO_2 emissions from vehicles worldwide – a business as usual scenario [1] vs. an emission reduction scenario (DLR)

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The activities at the Institute of Vehicle Concepts contribute to the sustainable development of technological systems for future generations of road and railway vehicles. The institute's contributions range from concepts and feasibility studies to the construction, calculation, and simulation of research demonstrators, components, and vehicles, as well as their presentation.

Author´s Biography

Professor Dr.-Ing. Horst E. Friedrich studied engineering at the Technical University of Munich. After working in the engineering and consultancy sectors, he took up a senior management position in the aeronautical industry in 1986. He was responsible for new methods of construction and new materials, aircraft engines and optimising product development times. In 1996, Prof. Friedrich joined Volkswagen AG in Wolfsburg as head of vehicle research, where at last he was head of Group research for materials technology and vehicle concepts. He specialised in innovative materials and construction methods, and concept vehicles for future vehicle specifications.

Since March 2004 he is director of the Institute of Vehicle Concepts at the German Aerospace Center in Stuttgart and professor at the University of Stuttgart. The research fields are Alternative Power Trains and Energy Conversion as well as Light Weight Design and Hybrid Construction methods.

Simone Ehrenberger is a researcher at the department of "Vehicle Systems and Technology Assessment" at the DLR Institute for Vehicle Concepts. Her research focuses on life cycle assessment of vehicle components as well as the economic assessment of new train concepts and their operational potentials. She graduated from the University of Karlsruhe in 2006 and holds a diploma in geoecology. Before joining the Institute for Vehicle Concepts, she worked on various projects in the field of life cycle assessment at the Karlsruhe Institute of Technology as well as the research group for material flow and resource management at the Institute of Applied Sciences at Pforzheim University.

e-mail: Horst.Friedrich@dlr.de