The Use of Hydrogen as an Energy Carrier for the Private and Public Transport Sector in Germany

by

Franc Grimm
Höhenweg 1a, 23617 Klein Parin, Germany

supervised by

Åhman, Max, 046-222 86 43
Department of Environmental and Energy Systems Studies
Bytaregatan 20, 222 21 Lund,
Max.Ahman@miljo.lth.se

Grubel, Holger, +49 40 - 63 96 30 05
Hamburgische Electricitäts-Werke AG
Überseering 12, 22 297 Hamburg, Germany
Electricity Generation and Transmission
Hydrogen and Fuel Cells
HGrubel@hew.de

Weinmann, Oliver, +49 40 - 63 96 34 50
Hamburgische Electricitäts-Werke AG
Überseering 12, 22 297 Hamburg, Germany
Electricity Generation and Transmission
Hydrogen and Fuel Cells

co-supervised by

Svenningsson, Per, 046-222 84 59
Department of Environmental and Energy Systems Studies
Tinghögvägen 40, 222 40 Lund,
Per.Svenningsson@miljo.lth.se
ACKNOWLEDGMENT

This Master of Science thesis was carried out at Lund University Master’s Programme in Environmental Science (LUMES) in cooperation with the German utility “Hamburgische Electricitäts-Werke” (HEW)

I am grateful to Max Åhman, Holger Grubel, Per Svenningson and Oliver Weinmann for their expert guidance and counseling during the accomplishment of this thesis and for the valuable information I received from them. I would also like to thank the staff of the department for their assistance and encouragement.

Finally, special thanks to both my girl-friend Ulrike for her moral support and Molly for the English corrections.
# Table of Contents

1. Introduction .................................................................................................................. 1  
   1.1 Objectives .................................................................................................................. 1  
   1.2 Methodology ............................................................................................................. 1  

2. Description of the Hydrogen Propulsion System ......................................................... 2  
   2.1 Primary Energy Source of Hydrogen ........................................................................ 2  
   2.2 Fuel Production Technology ................................................................................... 3  
   2.3 Vehicle Propulsion Technology .............................................................................. 3  
   2.4 Intermediate Energy Carrier .................................................................................... 3  

3. Description of German Initiatives and Case Studies ...................................................... 4  
   3.1 German Initiatives ..................................................................................................... 4  
      3.1.1 Activities of the Main Market Players in Germany ............................................. 5  
      3.1.2 Demonstration and Pilot Projects ...................................................................... 7  
   3.2 Case-Studies ............................................................................................................. 8  


5. Societal-Driven Requirements ...................................................................................... 12  
   5.1 Evaluation of the Hydrogen Propulsion System ...................................................... 12  
      5.1.1 Emissions .......................................................................................................... 13  
      5.1.2 Energy Efficiency ............................................................................................... 14  
      5.1.3 Material-Use ...................................................................................................... 15  
   5.2 Obstacles .................................................................................................................. 15  

6. Legal Requirements ..................................................................................................... 16  
   6.1 Analysis of the Environmental Policy Making Process ........................................... 16  
   6.2 Environmental Policy in the Transport Sector ........................................................ 16  
      6.2.1 Internalization of external Costs ....................................................................... 16  
      6.2.2 Environmental Regulations and Agreements .................................................... 17  
      6.2.3 Economic Incentives and Awareness Programs ............................................... 18  
   6.3 Evaluation of the Hydrogen Propulsion System ...................................................... 18  
   6.4 Obstacles – Legal Requirements .............................................................................. 19  

7. Customer Requirements ............................................................................................... 19  
   7.1 Description of the Customer Requirements ............................................................ 19  
   7.2 Evaluation of the Hydrogen Propulsion System ...................................................... 20  
      7.2.1 Technology ........................................................................................................ 20  
      7.2.2 Service-Infrastructure ...................................................................................... 22  
      7.2.3 Life-cycle Cost .................................................................................................... 23  
      7.2.3.1 Cost of the Fuel Cell Technology ................................................................. 23  
      7.2.3.2 Fuel Cost ........................................................................................................ 24  
      7.2.4 Availability ........................................................................................................ 26  
      7.2.4.1 Availability of Hydrogen ................................................................................ 26  
      7.2.4.2 Availability of Fuel Cell Vehicles ................................................................. 28  
      7.2.4.3 Willingness to Change and the need for Cooperation .................................. 28  
      7.2.5 Acceptance ........................................................................................................ 28  
   7.3 Obstacles – Customer Requirements ....................................................................... 29  

8. Action Plan for Implementation ..................................................................................... 31  
   8.1 Action Plan “City Buses” ............................................................................................ 32  
      8.1.1 Technological Strategy for Implementation ....................................................... 32  
      8.1.2 Scenarios ............................................................................................................ 33  
   8.2 Action Plan “Vans” .................................................................................................... 37  
   8.3 Action Plan “Passenger Cars” .................................................................................. 40  
      8.3.1 Technological Strategy for Implementation ....................................................... 40  
      8.3.2 Scenarios ............................................................................................................ 41  

9. Discussion ..................................................................................................................... 45
10. Conclusion .................................................................................................................. 47

References ...................................................................................................................... 48

Appendix I: Descriptions ............................................................................................... 51
Appendix II: Figures ......................................................................................................... 52
Appendix III: Demonstration and Pilot Projects ........................................................... 53
Appendix IV: Tables .......................................................................................................... 55
Appendix V: Scenarios - Figures .................................................................................... 58
Appendix VI: Stella Models ............................................................................................. 62
Appendix VII: Algorithms/Calculations/Operations performed by STELLA ................. 65

List of Figures

Figure 1.1: Specific Issues of the Thesis ........................................................................ 2
Figure 2.1: Technological Paths of Hydrogen ................................................................. 2
Figure 4.1: Technology Push and Demand Pull Factors of the Hydrogen Propulsion System ................................................................. 10
Figure 4.2: Comprehensive Analysis of HPS in terms of Implementation Possibilities ..................................................................................... 11
Figure 5.1: Interrelation between the Environment and Road Traffic in General ......... 12
Figure 6.1: Analysis of the Environmental Policy Making Process ............................. 16
Figure 8.1: Possible and Suggested Entire Chain of the Hydrogen Propulsion System - City Buses ................................................................. 32
Figure 8.2: Switch to Hydrogen: Scenario "Business as usual" - City Buses .................. 34
Figure 8.3: Action Plan "City Buses" - Scenario "Business as usual" ............................ 35
Figure 8.4: Switch to Hydrogen: Scenario "Strong-man Act" - "City Buses" ................. 36
Figure 8.5: Action Plan "City Buses" - Scenario "Strong-man Act" .............................. 36
Figure 8.6: Switch to Hydrogen: Scenario "Business as usual" - "Vans" ....................... 38
Figure 8.7: Action Plan "Vans" - Scenario "Business as usual" .................................... 38
Figure 8.8: Switch to Hydrogen: Scenario "Strong-man Act" - "Vans" ......................... 39
Figure 8.9: Action Plan "Vans" - Scenario "Strong-man Act" ..................................... 40
Figure 8.10: Possible and Suggested Entire Chain of the Hydrogen Propulsion System - Passenger Cars ................................................................. 40
Figure 8.11: Switch to Hydrogen: Scenario "Business as usual" - "Passenger Car" powered by GH2 ................................................................................. 42
Figure 8.12: Implementation Obstacles of CGH2 Powered Passenger Cars - Scenario 1 ................................................................................................. 43
Figure 8.13: Switch to Hydrogen: Scenario 2 - "Passenger Car" powered by Gaseous Hydrogen ..................................................................................... 44
Figure 8.14: Implementation Obstacles of CGH2 Powered Passenger Cars - Scenario 2 ................................................................................................. 44
Figure A.I.1: Emissions of the Road Traffic and their Effects on Environment ............ 51
Figure A.I.2: The Function of the Fuel Cell Technology ................................................ 52
Figure A.I.3: The entire Product Life Cycle of several Technologies ......................... 52
Figure A.III.1: NEBUS ................................................................................................. 53
Figure A.III.2: The 4 Versions of NECAR .................................................................... 53
Figure A.III.3: W.E.I.T. Project Hydrogen-Energy Iceland-Transfer ......................... 54
Figure A.V.1: Switch to Hydrogen: Scenario "Decrease of the Green Tax in the Public Transport Sector" ................................................................. 58
Figure A.V.2: Action Plan "City Buses" - Scenario "Decrease of the Green Tax in the Public Transport Sector" ................................................................. 58
Figure A.V.3: Elements of Costs (in Pf per km) - Scenario "Business as usual" - "City Buses" ................................................................. 59
Figure A.V.4: Elements of Costs (in Pf per km) - Scenario "Business as usual" - "Vans" ................................................................................................. 59
Figure A.V.5: Switch to Hydrogen: Scenario "Business as usual" - "Passenger Car" powered by LH2 ................................................................................. 59
Figure A.V.6: Implementation Obstacles of LH2 Powered Passenger Cars - Scenario 1 ................................................................................................. 60
Figure A.V.7: Switch to Hydrogen: Scenario 2 - "Passenger Car" powered by LH2 ................................................................................................. 60
Figure A.V.8: Implementation Obstacles of LH2 Powered Passenger Cars - Scenario 2 ................................................................................................. 60
Figure A.V.9: Switch to Hydrogen - Scenario "Business as usual" - "City Buses" ............ 61
Figure A.VI.1: Stella Model - City Buses ....................................................................... 62
Summary

Hydrogen as a new energy carrier in the private and public transport sector could provide huge potentials to reduce the impacts on the social and ecological environment without affecting the national economy negatively. Accordingly, the use of hydrogen would lead to a reduction of harmful emissions to zero (during the usage) and to a higher material and energy efficiency per service unit over the entire life-cycle compared to conventional fuels like gasoline and diesel. In addition, it would make it possible to use renewable energy sources in the transport sector.

Despite of the ecological benefits of hydrogen, there are several considerable barrier to entry. In general, these are mainly higher life-cycle cost, the absence of the wide-spread refueling infrastructure and the technological problem of storing hydrogen onboard a vehicle. But there are not just technological difficulties to overcome. There are also different blocking coalitions who are able to continue delaying the introduction of stricter emissions standards and legal requirements, which would support the market introduction of hydrogen. Under these circumstances, a market introduction of hydrogen is unlikely in a short and medium term unless changes can be made in the cost structure and policy making process. If sustainability becomes a real political driver the chances for an accelerated market introduction of hydrogen into the transport sector become greater.

Accordingly, a shift of the current transport system towards a more sustainable system based on hydrogen is mainly dependent on the willingness to change of the main market players, especially of the German Government. To accomplish the transition a cooperation between the main market players and an agreement about hydrogen as the common uniform energy strategy for the transport sector in Germany are necessary. Furthermore, the economic system of pricing, subsidizing and charging the transport system need to be changed. It is essential that several demand pull and technology push strategies are addressed simultaneously from different sites.
1. Introduction

Atmospheric pollution is one of the main issues regarding the occurrence of contemporary environmental problems like smog, acid rain, stratospheric ozone depletion and climate change (the greenhouse effect). To a large degree, this is caused by emissions from combustion engines in vehicles (Bossel, 1994).

As a result of both environmental problems and new legislation, the industry, especially oil-companies and car-manufacturers, are looking for new environmentally-sound technologies in the transport sector. A promising technology that will be developed is a hydrogen propulsion system for vehicles. Hydrogen-powered vehicles have the potential to provide engine performance comparable to a conventional combustion engine without creating harmful tail-pipe emissions of any kind. In fact, the only by-product of hydrogen-powered vehicles is water vapor.

1.1 Objectives

The purpose of this thesis is to analyze the use of hydrogen as an energy carrier for the private and public transport sectors in Germany. I plan to examine the issues of implementation possibilities and obstacles with respect to the societal-driven, legal and customer requirements, in order to develop a set of strategies and measures on how to implement the hydrogen propulsion system (action plan). More specifically, the defining problems of the paper are: What are the obstacles and possibilities of implementing it? What kind of weaknesses and strengths does the technology have? And, how to implement it?

This thesis is not aiming at the development of a sustainable private and public transportation system, which would make it necessary to consider the entire traffic system, including the city-planning activities and alternative transportation systems. On the contrary, the scope of this study is limited to the effects of the usage of hydrogen as an alternative fuel for vehicles. Thereby, the overriding aim of the thesis is to redesign the automotive road traffic system in a more environmentally-sound way.

1.2 Methodology

In order to achieve the goal mentioned above, the thesis is based on the following research activities: a literature review, a survey of both the present state of technology (prototypes) and realized applications of hydrogen in the transport sector (pilot projects), and an analysis of three different case studies (see descriptions below).

The concepts of systems analysis and systems thinking (including the computer modeling tool “Stella”) are used to analyze the effects and implementation possibilities of the hydrogen propulsion system in an interdisciplinary and comprehensive way. Thereby, all kinds of aspects and their interrelations are considered, including social, ecological, technical and economic aspects. The interrelations and interactions are illustrated in a causal loop diagram in chapter 4. This causal loop diagram describes the mental model of the author concerning the interrelations and interactions within the complex system. The aim of this concept is to provide a higher transparency of analysis and to make it more understandable.

The thesis work has been narrowed down to one specific vehicle propulsion technology (PEMFC) and to a couple of onboard storage systems (the use of both liquid and compressed gaseous hydrogen). The explanations for these limitations and preferences are given in chapter 2. In addition, the scope of this study is limited to three different case studies (market
sectors) – namely “City Buses”, “Vans” and “Passenger Cars”. The case studies were carried out by the author in cooperation with the utility “Hamburgische Electricitätswerke AG”, the public transportation company “Hamburger Hochbahn AG” and the parcel service company “Hermes Versand Service” in order to analyze both the technology and the possibilities for its application in the three different market sectors. The scope of the study is illustrated in figure 1.1.

![Figure 1.1: Specific Issues of the Thesis](image)

2. Description of the Hydrogen Propulsion System

2.1 Primary Energy Source of Hydrogen

Hydrogen is the simplest naturally occurring element that can be derived from a variety of energy sources like natural gas, methanol, biomass, and water. Due to the fact that hydrogen is an energy carrier but not a natural energy source, it must be produced alternatively from renewable and non-renewable energy sources through the use of different technologies (Hart, 1997; Wagner/Geiger/Reiner, 1996). The following figure illustrates the possible technological paths from the production of hydrogen based on primary energy sources to the utilization of the energy carrier as a fuel for vehicles.

![Figure 2.1: Technological Paths of Hydrogen](image)
In addition, hydrogen is currently produced as a by-product from refineries, electrolytic production (mostly from hydro power), or from other chemical surplus production (mostly chlorine-alkaline-electrolysis; Altmann, 1997).

2.2 Fuel Production Technology
Figure 2.1 shows the most commonly used methods of hydrogen production, which are: (Hart, 1997; Wagner/Geiger/Reiner, 1996)

- **Electrochemical processing**: The electrochemical process of producing hydrogen is driven by electricity, which can be based on both renewable and non-renewable energy resources. Hydrogen is formed by splitting water through the use of electrolysis. The energy efficiency of this process is quite high and it can be significantly improved (up to 90%) in the future by using high pressure and high temperature electrolysis.

- **Petrochemical processing**: Currently, hydrogen is mainly produced by petrochemical processing like steam reforming based on natural gas. Compared to the electrochemical process, this petrochemical process is characterized by a higher level of greenhouse emission.

- **Gasification**: The gasification process is based on both non-renewable (e.g. coal) and renewable energy resources like biomass. The gasification process is mainly developed to produce hydrocarbons; hydrogen is only produced as a by-product.

2.3 Vehicle Propulsion Technology
Hydrogen can be used in both fuel cells and combustion engines. Fuel cell technology makes it possible to convert the chemical energy of fuels directly into electricity resulting in a higher energy efficiency. Today, most of the ongoing development programs for automotive fuel cell technologies are concentrating their efforts on the "Proton Exchange Membrane Fuel Cell" (PEMFC) technology, because of the good performance and the better prospectives (DaimlerChrysler, 1999 a; Hydrogen & Fuel Cell Letter, July 1999). In addition, the PEMFC technology seems to be the fuel cell that comes closest to the point of meeting societal-driven and customer requirements at the present time. For this reasons, this thesis is focused on the PEMFC technology. The function of the PEM fuel cell is shown and explained in figure A.II.1 (Appendix). Combustion engines are not considered in the following analysis because of both the low energy efficiency of converting chemical bound energy into mechanical energy, and comparatively high level of air-pollution in relation to the PEMFC technology.

2.4 Intermediate Energy Carrier
The PEMFC technology requires an onboard storage of hydrogen or hydrocarbons. Basically three fuel onboard storage approaches for fuel cell vehicles can be differentiated (Wurster, 1997):

- "hydrogen storage in compressed gaseous (high pressure tanks, metal hydrides, graphite nanostructures) or liquid form (cryogenic liquid, cryoadsorption) [potentially from renewables sources – potentially without any emissions]
- hydrogen storage in hydrogen rich liquid methanol [potentially from renewable sources – potentially with very low emissions]
- hydrogen storage in hydrogen rich hydrocarbons such as gasoline or diesel [only from fossil sources – with emissions]"

Many automotive fuel cell projects currently seem to favor methanol as a fuel for fuel cell powered cars (Kalhammer et al., 1998; DaimlerChrysler, 1999 a; Hydrogen & Fuel Cell
Letter, July 1999). This could be explained by the economic and technical advantages of methanol in terms of the required distribution structure. Methanol can easily be stored onboard the vehicle and its distribution structure would be similar to conventional fuels like gasoline. This is a costs advantage at least in a short-term view. In contrast to this, the use of an onboard methanol fuel processor would increase the complexity, weight, volume and costs of the fuel cell propulsion system. In addition, it would also reduce the fuel cell system efficiency and load response, and its operation could result in some, although generally low, emissions of NOx and HC (Jung, 1999). Due to the better performances regarding energy efficiency and zero emission standard, only the following two types of onboard storage systems are considered in this thesis: the use of both compressed gaseous hydrogen and liquid hydrogen.

3. Description of German Initiatives and Case Studies

3.1 German Initiatives

Hydrogen propulsion systems are seen as promising technologies in a medium and long term view. Therefore, several automobile manufacturers (DaimlerChrysler, General Motors, Ford, Daimler-Benz, Toyota, Mazda, Honda and Nissan) have announced that they plan to commercialize PEM fuel cell cars around 2004-2005. Concerning the huge market potential, almost every car manufacturer is trying to be the first in the world to offer a series-produced fuel cell vehicle. But also oil giants like Shell believe "hydrogen is the long-term fuel of the future" (New Scientist, May 1999). The driving force behind Shell is finding new promising products for the future. At present, Shell is faced with the fact that its prime product (crude oil) is facing the twin pressures of the need to reduce emissions of greenhouse gases and a decline in known oil reserves (New Scientist, May 1999). Therefore, Shell, in order to be able to meet requirements regarding low emission capability of fuels in the future, is looking for new and environmentally-sound fuel. In addition, the expected scarcity of crude oil in the future, which will result in higher prices, is another main driving force for oil-companies. Despite the lack of infrastructure and the expansiveness of the hydrogen propulsion system, almost all car manufactures and oil companies are not only interested in making an effort to introduce the hydrogen propulsion system, they are eager to be the first market player; the so-called innovator. The driving force of the innovator strategy is becoming a market leader in the new promising market section in order to:

- gain a competitive advantage (see for further information: Porter, 1986) in terms of societal-driven, legal and customer requirements;
- make higher profits through the rent of innovation (Pfeiffer et al., 1991; Porter, 1986);
- improve the image of the company as innovative and environmental-friendly;
- be able to build up market barriers for the followers and imitators by using the "Henderson-Curve", the so-called learning curve (see for further information: Henderson, 1984).

Due to the new needed production and distribution system of hydrogen, new market players will enter the fuel market in the field of road traffic. For instance, utilities like HEW can use their knowledge about energy and hydrogen production in the new market segment. Therefore, the philosophy of HEW is to take part in the overall development by specifically addressing questions of infrastructure and public acceptance of hydrogen as an energy carrier. By doing this they hope to become an important market player in the field of utilizing and supplying hydrogen (Weinmann, 1999).
3.1.1 Activities of the Main Market Players in Germany

Important projects and market players are:

**DaimlerChrysler**

The DaimlerChrysler Fuel Cell Project is aiming at the development and commercialization of PEM fuel cell propulsion systems for cars (NeCar – New electric Car) and buses (NeBus – New electric Bus). Therefore, a joint venture between Daimler-Chrysler, Ford Motor Co. and Ballard Power System has been established. Together they will invest approximately DM 900 million to DM 1.9 billion for the time period 1992-2004. The project is focused on the development of the PEM fuel cell technology including three types of fuels: direct hydrogen supply and on-board storage (gaseous hydrogen), methanol on-board reforming and gasoline onboard catalytic partial oxidation (Hydrogen & Fuel Cell Letter, 01/99 and 04/99; DaimlerChrysler, 1999 b; Ludwig-Bölkow-Systemtechnik GmbH, 1999 a). NeBus is a fuel cell version of Daimler-Benz’ O 405 N model, a 12-meter, low-floor city bus with 34 seats plus standing room. NeBus is driven by compressed gaseous hydrogen which is carried in seven 150 liter, 300 bar roof-mounted gas bottles that hold about 45,000 liters of CGH2, which is sufficient for up to 250 km (DaimlerChrysler, 1999; Hydrogen & Fuel Cell Letter, June 1997). NeBus is described in section 7 and shown in section Appendix III. The market introduction of NeBus will be attained through the following phases: (Ebner 1999; DaimlerChrysler, 1999 c; Hydrogen & Fuel Cell Letter, November 1999)

**Phase 1 (1997-1998):** Proof of Concept (seven prototype-buses)
**Phase 2 + 3 (1999-2002):** Demonstration and Testing Projects
**Phase 4 (2002):** Full Commercial Production

According to Pow (Hydrogen & Fuel Cell Letter, November 1999), the company dbb fuel cell engines, inc. (the Ballard/DaimlerChrysler/Ford joint venture that will build fuel cell engines for cars, busses, and trucks) is now working on plans to build an engine plant with a capacity of 500 engines per year. In the first year, the output level will be lower than that. The full output is expected to be reached about 2006 or 2007.

NeCars are planned to have methanol on-board reforming first, and POX-on-board hydrogen supply from gasoline later. The direct hydrogen supply and on-board storage system will not be considered at the beginning because of the missing refueling infrastructure. NeCar shall enter the market by 2004. The following manufactured units are set to be sold in the market partially in Mercedes and Ford passenger cars, and to third party car manufacturers (Ludwig-Bölkow-Systemtechnik GmbH, 1999 a):

- **Year 2004:** 40,000 units
- **Year 2005:** 70,000 units
- **Year 2006:** 100,000 units

The four different versions of NeCar are shown in section Appendix III.

**BMW**

The hydrogen project of BMW is aiming at the development and commercialization of hydrogen-driven passenger cars, presently on the basis of the latest 7-Series models. BMW is focusing their development activities on the following two types of propulsion systems: a conventional combustion engine with direct transmission and a so-called "cold" combustion of fuel cell technology. As motive power, BMW favors the combustion engine because of the
lower expenses, more power and less weight. Currently, liquid hydrogen is stored in a vacuum-insulated 140 liter tank in the luggage compartment at a temperature of approximately -250°C. BMW began to start the development activities in the late seventies. Development has now reached the fifth generation of hydrogen-driven passenger cars. The vehicles are currently produced in small series production. The following manufactured units are set to be introduced into the market in the following years (Steffes, 1999; BMW, 1999 a and b):

Year 2000: 15 units – small serial-production; the vehicles will be used for transporting people at the EXPO 2000 in Hanover (shuttle-service); the project is aiming at demonstrating the technology under real day-to-day driving conditions.

Year 20??: the serial production will be start after the development of the refueling infrastructure; the exact date is uncertain and speculative as of yet.

**MAN**

The hydrogen project of MAN Nutzfahrzeuge AG is aiming at the development and commercialization of a hydrogen powered MAN low-floor bus for regular operation in urban areas. The development activities are focused on the PEM fuel cell technology. The hydrogen will be supplied to the fuel cell from a gas storage system on the roof of the bus – in a form of compressed gaseous hydrogen at a pressure of 250 bar. The storage system will be comprised of 9 cylinders for a total of 1548 liters geometric volume, ensuring an operating range of around 250 km (MAN, 1999). The market introduction of the hydrogen-powered MAN bus will be attained through the following phases (Schaller, 1999; MAN – Press release, 1999):

Phase 1 (1996-1999): Pilot-projects at the Munich Airport and in Bavaria (described below)

Phase 2 (2000): Demonstration and testing projects in Berlin, Lisboa and Copenhagen under real day-to-day conditions

Phase 3 (2000 –5): Demonstration of single city buses and fleets under real day-to-day driving conditions


**Development of a new Energy Strategy in the Transport Sector**

The ongoing negotiation between the main four German car manufacturers (DaimlerChrysler, Volkswagen AG, BMW and MAN), three oil/fuel companies (Shell and Aral) and one utility (RWE) are aiming to achieve an agreement about a common uniform energy strategy for the transport sector in Germany. The more specific central problem is to get a consensus on defining the fuel of the future for the transport sector. Furthermore, the expansion of the defined strategy in the European transport system is planned to occur after a successful implementation of the strategy in Germany. The result of the cooperative work, which can be expected at the end of this year, will be presented to the German Chancellor Schröder at the end of November in order to coordinate the industrial and political efforts of reorganizing the current transport sector towards a more sustainable future. The current state of the negotiation process is "top secret" and therefore unknown. But it can be expected that the cooperation will prefer propulsion systems and fuels which are applicable for general purposes like the fuel cell technology powered by methanol and hydrogen based, for instance, on natural gas through steam reforming. Furthermore, it seems to be that the cooperation will not consider
natural gas (in combination with a combustion engine) and liquid hydrogen as new fuels in the negotiation process any longer.

3.1.2 Demonstration and Pilot Projects

Several demonstration projects are planned for the operation of hydrogen-powered low floor city buses in Germany. One example is the planned operation of three MAN 12 low floor city buses with internal combustion engine and compressed gaseous hydrogen storage by the municipal bus operator Stadtwerke Karlsruhe by the year 2001 (Ludwig-Bölkow-Systemtechnik GmbH, 1999a). In addition, there are a few already realized projects in Germany. In the following section, the three main ongoing demonstration projects are described.

W.E.I.T. Project Hydrogen-Energy Iceland-Transfer

13 companies, mostly located in Hamburg (for instance HEW and Hermes Versand Service), have agreed on a joint venture to operate a hydrogen-powered van in their vehicle fleets. The Mercedes-Benz vehicle model "Sprinter", which is shown in figure A.III.3, is driven by gaseous hydrogen and an internal combustion engine. During phase 1 of the project, the needed hydrogen is produced as a by-product from chemical surplus production (mainly from Dow Chemical at Stade near Hamburg). In phase 2 of the project, it is intended to import hydrogen (based on hydro power) from Island. Thus, the whole chain of a clean energy carrier in modern traffic will be achieved and demonstrated. The project was initiated by the Hamburger Wasserstoff-Gesellschaft e.V. and is managed by the Hamburger Wasserstoff-Agentur (HaWA). The operation of the first fleet vehicle and fuel station started at the end of 1998. In the near future, 5 further vehicles will be put into operation. The aims of this demonstration project are: to increase the knowledge and the acceptance of hydrogen (through public relation, demonstration and pilot projects), to realize a part of the hydrogen infrastructure, to show (on a medium term basis) a whole energy chain based on renewable energy from Island, to reduce emissions, and to demonstrate their capability to fulfill the customer requirements under real day-to-day driving conditions (Weinmann, 1999; Hamburger Wasserstoff-Agentur (HaWA), 1998). The project is financed by private capital. The detailed project investment cost for the six vans and the refueling station amounts to slightly above 1 million DM. One of the driving forces behind the project is the self-obligation of the Hermes Versand Service (which belongs to OTTO Versand – Europe’s largest mail order house) to save 25 % CO₂ by 2005 (on the basis of 1990 values). The aim of this self-obligation is to achieve a competitive advantage through a higher environmentally-friendly image (Ludwig-Bölkow-Systemtechnik GmbH, 1999a).

ARGEMUC – Munich Airport Hydrogen Project

A public filling station for liquid and gaseous hydrogen with on-site hydrogen gas production was opened on 5th of May 1999 at the Munich International Airport. The project is testing the fully automatic refueling of cars with liquid hydrogen and the use of one NEOPLAN and two MAN low-floor airport buses for passenger transport under the safety requirements of an international airport. The two low-floor airport shuttle buses are powered by gaseous hydrogen produced by electrolysis used in an internal hydrogen engine. The gas storage tank, mounted on the vehicle roof, consists of 15 aluminum vessels with fully wound carbon-fiber jackets characterized by a storage capacity of 2580 liters of hydrogen at a pressure of 250 bar. This volume is sufficient for an uninterrupted daily operation at the Munich Airport (H2MUC, 1999). The price for the needed gaseous hydrogen equals 0.65 German marks per standard cubic meter, which is equivalent to 0.3 liters of conventional diesel fuel (ARAL, 1999). In addition to the shuttle buses, a liquid hydrogen powered vehicle (BMW 7-Series) is...
also used within the passenger service area for transporting people. The fuel tank (a 120-liter liquid hydrogen tank) permits a range of about 300 km. The vehicle can be refueled either automatically by a robot dispenser at the airport, or manually at BMW (H2MUC, 1999). The price for a liter of hydrogen amounts to 1.10 German marks (which is equivalent to around 0.3 liters of conventional gasoline), however this covers only the production costs (ARAL, 1999). The aim is to gain insights into the daily use and economic feasibility of the hydrogen propulsion system. The hydrogen project at Munich Airport has been realized by 14 industrial companies (Aral, BMW, MAN-Nutzfahrzeuge, Siemens and HEW for instance). The project is financed by private capital (50%) and public money (50%) by the federal state of Bavaria. The detailed project investment costs amount to approximately 34 million DM (Ludwig-Bölkow-Systemtechnik, 1999a).

Liquid Hydrogen Bus Demonstration in Bavaria
In April 1996 the world's first liquid hydrogen powered demonstration bus began carrying paying passengers on a regular city route in Erlangen, a small Bavarian university town in southern Germany (Hydrogen & Fuel Cell Letter, May 1996). The bus underwent a two-year test: the first eight months in Erlangen, followed by two similar test periods in Munich as an airport connector linking Munich with its International Airport. The MAN bus is powered by a dual-fuel-liquid hydrogen and gasoline – 12 liter 6-cylinder internal combustion engine. The achievable range of the hybrid bus is about 450 km with gasoline and about 250 km with hydrogen. The maximum speed is 89 km/h. The 3.1 million DM project was financed jointly by the state of Bavaria, which was paying for slightly more than half of the cost, and the European Union. The demonstration project was aiming at getting information about the feasibility of a liquid hydrogen internal combustion engine bus in regular public demonstration including refueling infrastructure and licensing of all hydrogen specific components (Hydrogen & Fuel Cell Letter, May 1996; Ludwig-Bölkow-Systemtechnik GmbH, 1999a).

3.2 Case-Studies

- Case-Study 1: City Buses (Hamburger Hochbahn AG)
The city buses are owned and operated by the public transportation company of Hamburg, called "Hamburger Hochbahn AG". The Hamburger Hochbahn AG operates three U-Bahn (metro) lines and 102 bus routes, carrying more than one million passengers every day and around 400 million passenger every year. Each year the buses cover around 51 million kilometers and at times there are up to 110 trains operating simultaneously on the 101-kilometre network, carrying nearly 180 million passengers a year. The bus-fleet consists of around 600 buses. Two-thirds of the fleet consists of comfortable low-floor buses characterized with a total life-time of 12 years (14 years in the future). In order to reduce emissions, the buses are powered by low-sulfur diesel, and are fitted with up-to-date engines specially designed to reduce fuel consumption. In addition, the Hamburger Hochbahn AG is assisting in the development of hydrogen-powered vehicles that will reduce emissions to zero. A demonstration project is planned for the operation of approximately 8 hydrogen-powered city buses in Hamburg by the year 2001 (Hamburger Hochbahn AG, 1999). In general, around 82,000 buses were in use in Germany in 1997. The buses are mainly powered by diesel and only a very low percentage are powered by alternative fuels in Germany (Kraftfahrt-Bundesamt, 1998).

- Case-Study 2: Passenger Cars
Passenger cars represent the largest and potentially the most attractive market for the hydrogen propulsion system. In 1997, 712,268 vehicles were used in Hamburg and
41.673.787 in Germany. This implies a change of + 0.7 % from the corresponding period of the previous year (Kraftfahrt-Bundesamt, 1998). According to a Shell study (Shell, 1995), the following two different scenarios for the further development of the rolling stock are possible:

**Scenario 1:** The rolling stock will increase by 8 million to 49 million vehicles by the year 2010 due to both the increase of the population size in Germany, which would be responsible for an increase by 3 million vehicles, and a higher demand per person. After this, the rolling stock will increase by another 1 million vehicles by the year 2020. This rolling stock of 50 million vehicles will stabilize in the following decades due to a stable number of adults and a stable level of demand per person.

**Scenario 2:** In this case, the rolling stock will increase by 5 million vehicles by the year 2010 due to the lower increasing rate of both the population size in Germany, which would be responsible for an increase by 2 million vehicles, and the demand per person compared to scenario 1. After this, the rolling stock will decrease by 1 million vehicles per year to 44 million in 2020 due to a decrease in both the total number of adults and demand per person caused by new legal regulations like the green-tax.

Most passenger cars are still powered by gasoline. The statistic of registration of new passenger cars illustrates a trend characterized by an increasing rate of diesel vehicles and a decreasing rate of gasoline vehicles. As of yet, only a few vehicles are powered by alternative, environmental-friendly fuels in Germany (Kraftfahrt-Bundesamt, 1998).

**- Case-Study 3: Vans (Hermes Versand Service)**
Concerning the medium-duty trucks sector, a fleet of the private company "Hermes Versand Service" was chosen. The Hermes Versand Service offers in-house delivery service mainly for a major mail-order company, called OTTO. The fleet consists of 1.800 vans (medium duty truck: 3.5 tons) which are located in 64 depots all over Germany. Each year the vans are used for around 63-70 million kilometers. Most of the vans are powered by diesel and only 13 vans are powered by natural gas. In addition, the Hermes Versand Service is operating one vehicle driven by a hydrogen-based combustion engine (Schuldt, 1999). In general, the total amount of vans in Germany will increase in the future due to the increase of mail-order business like Internet (Bartke,1999). Currently, 1.902.627 trucks are used in Germany. The trucks are mainly powered by diesel and only a very low percentage is powered by alternative fuels in Germany. The statistic of the registration of new trucks illustrates a trend characterized by an increasing rate of diesel vehicles and a decreasing rate of gasoline vehicles. In addition, it illustrates a very low rate of increase in alternative propulsion systems such as natural gas (Kraftfahrt-Bundesamt, 1998).

**4. Systems Analysis of the Hydrogen Propulsion System**
In general, the implementation of hydrogen propulsion systems into the transport sector depends on two driving forces for innovation: *demand pull and technology push factors* (Holt, 1987; Zahn/Schmid, 1992). The technology push factors are external driving forces on the policy of a company, such as new governmental regulations on road traffic or environment (*legal requirements*). These external forces push a company to develop and produce more environmentally-sound products and therefore alter (or influence) the company policy. Other push factors could be actions by non-governmental-organizations, mass-media or civic action groups in order to ensure the fulfillment of the *societal-driven requirements*. For example, protest and boycott activities in Germany against Shell have caused the mineral-
oil-giant to reconsider their plan to sink the offshore "Brent-Spar" in 1994. Finally, the policy making process of a company can also be influenced by competitors through the development and promotion of new environmentally-sound products and technologies (market requirements; Müllner, 1995; Steger, 1993, Zahn/Schmid, 1992). For this reason, a company can not longer be seen as an independent player in a market. It is rather an open-system, which means that a company has to take into consideration all kinds of technology push factors in the policy making process in order to be successful in the market.

The demand pull factors can be seen as market potentials. This could be a change of current customer requirements on products. These new requirements offer a potential for new products, therefore pulling the companies to develop new technologies for the market. A new demand for environmentally-sound products, for example, can change the entire market sector and the competitive situation in a short and medium term. For instance, the supply of the first CFCs-free freezer and refrigerator produced by the German company FORON caused a change of both the customer requirements and the entire market sector within a couple of years. Therefore, the policy making process of a company has to be dependent on the customer requirements. Only the fulfillment of the customer requirements can ensure the success of a new product in a market. The demand pull and technology push factors are summarized in figure 4.1.

![TECHNOLOGY PUSH DEMAND PULL](image)

Figure 4.1: Technology Push and Demand Pull Factors of the Hydrogen Propulsion System

The above figure shows the hydrogen propulsion system, its driving forces and the main market players. These terms can be seen as elements (or subsystems) of the entire market system characterized by high complexity. In order to understand the complexity of the problem and the interrelationships between the above-described elements, a causal loop diagram has been developed which is shown in figure 4.2. By doing this, several aspect have been taken into account including social, technical, economic and ecological aspects. The following different actors have been identified: the producer of the hydrogen propulsion system and its competitors, the government, the customer, the society and the environment. The summarized explanation of the causal loop concept is shown in Appendix I.

As figure 4.2 shows, the success of the hydrogen propulsion system in the market is mainly dependent on its competitive advantages in comparison to its competitors. According to Porter (1986), competitive advantages can only be attained through the use of the following three strategies: cost control (cost advantage), differentiation and focus on priorities (qualitative advantage). A cost control-oriented company aims at a reduction of the total life-cycle cost of a product in order to offer products characterized by the lowest market price.
The strategy "differentiation" aims at the development of at least one unequaled qualitative attribute of the product, which cannot be fulfilled by the competitors. The goal of the third strategy is the concentration on niche markets. All strategies have in common the ability to create a competitive advantage in the market provided that other aspects of the chosen strategy will not be neglected. This means that for instance the strategy "differentiation" should also take into consideration the cost situation of the company. Higher costs can destroy the qualitative advantage of a company (Porter, 1986). Therefore, a market player has to choose one competitive strategy in order to be the best in one specific area without neglecting the other customer requirements. In general, the customer requirements are low life-cycle costs and specific qualitative attributes of the product. The customer qualitative requirements of the hydrogen propulsion system can vary for different customers (Government, industry or private persons) and applications such as cars, trucks or buses. These requirements can also be influenced by legal and societal-driven requirements, which are dependant on the citizens and their values, way of thinking and behaviour.

![Diagram of comprehensive analysis of HPS in terms of implementation possibilities](image)

**Figure 4.2: Comprehensive Analysis of HPS in terms of Implementation Possibilities**

According to the aforementioned comprehensive analysis of implementation possibilities of the hydrogen propulsion system, it is necessary to assess and evaluate the hydrogen propulsion system in terms of

- societal-driven requirements,
- legal requirements and
- customer requirements

compared to the conventional technologies (market requirements) in terms of both the current and future state of development, in order to be able to develop a set of strategies and measures on how to implement it. Therefore, the following sections are dealing with these three different types of requirements. By doing this, it is also considered that conventional technologies will still be further developing by the time fuel cell vehicles penetrate the market.
5. Societal-Driven Requirements

The societal-driven requirements depend on the citizens of a specific country or area and their values influenced by different actors like Governmental or Non-Governmental Organizations. Therefore, the requirements are variable and once defined requirements are just partly applicable for the worldwide market sector. For this reason, the scope of this thesis is narrowed down to the transport market sector in Germany.

Aside from a high standard of prosperity, the protection of the ecological and social environment is a major concern of the German society. This is reflected in various surveys of the citizens carried out, for instance, by Rolke (1994) and Fricke (1996). The increased awareness of environmental problems within the society, which is based on environmental awareness and education programs of both Governmental and Non-Governmental Organizations, will influence the policy of the German government (indirect effect on the industry; see chapter 6) and the industry (direct effect on the industry; see chapter 7) in the future.

In the following sections, the hydrogen propulsion system is assessed in terms of the current environmentally oriented societal-driven requirements and in the future. By doing this, the performance of the hydrogen propulsion system is compared to its competitors.

5.1 Evaluation of the Hydrogen Propulsion System

The following figure illustrates the interrelation between the environment and road traffic in general.

![Interrelation between the Environment and Road Traffic in General](figure5_1.png)

Figure 5.1: Interrelation between the Environment and Road Traffic in General

The following analysis is focused on the energy intensity and emissions of the different technologies. Other kinds of environmental impacts can be untreated in the following comparison because of both the similar effects of the technologies with respect to waste, land use and accidents and the lack of data (material intensity). The analysis contains a comprehensive calculation of both the total emissions and the material and energy intensity from the cradle (extraction) to the crave (final disposal). This means that the entire product lifecycle as well as the total number of units of service extracted are considered. The entire product lifecycles of the different technologies are demonstrated in figure A.II.2.
5.1.1 Emissions

The results of the analysis of total emission with respect to the entire generation and distribution process (from extraction to the provision of the energy carrier) are shown in table A.IV.1 (see also figure A.I.2: emissions of the road traffic and their effects on the environment). The analysis, which was carried out by the Ludwig-Bölkow-Systemtechnik GmbH (1996) contains three scenarios with different time-scales in order to take into consideration the different states of technology in a short- (0-5 years away), medium (5-10 years away) and long-term view (10 and more years away).

Accordingly, the production process of gaseous hydrogen is characterized by the lowest level of emissions provided that hydrogen is based on renewable energy sources like wind and water. The production of gaseous hydrogen would lead to a reduction of both CO2-emissions and CO2-equivalent emissions by 50-80 % compared to the production of conventional fuels. Despite the fact that the production of gaseous hydrogen requires additional processes to transform electricity (which could be used for energy end-use technologies as well) into a gaseous form, the use of gaseous hydrogen in the transport sector could minimize the emissions during the generation process in comparison to conventional fuels. This could be traced back to the low-emission standard of the required conversion technologies (wind and hydro power plant). In contrast to this, the production of liquid hydrogen would lead to a higher short-term emission level due to the need for an additional energy intensive process to liquefy hydrogen. This process will be optimized in a medium and long-term view through an improvement in the technology (higher energy efficiency). In this case, the level of emission could be comparable to the production process of gaseous hydrogen based on wind-power. Due to the low state of technology, the material and energy intensive production of solar-power is not competitive with the other kind of technologies in the short and medium-term in regards to the emission level of the entire generation process.

Emissions during Usage

Table 5.1 shows the expected emission standard of vans in terms of the different state of technologies in the future. Despite the fact that this table shows only the emission standard of vans, the same trend can also be expected for the "City-Buses" and "Passenger Cars" market sectors.

<table>
<thead>
<tr>
<th></th>
<th>CO (g/km)</th>
<th>HC + NOx (g/km)</th>
<th>Particles (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Diesel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>0,6</td>
<td>1,20</td>
<td>0,17</td>
</tr>
<tr>
<td>- medium-term</td>
<td>0,6</td>
<td>0,60</td>
<td>0,09</td>
</tr>
<tr>
<td>- long-term</td>
<td>0,5</td>
<td>0,20</td>
<td>0,03</td>
</tr>
<tr>
<td><strong>Gasoline</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>1,4</td>
<td>0,50</td>
<td>0,00</td>
</tr>
<tr>
<td>- medium-term</td>
<td>1,4</td>
<td>0,35</td>
<td>0,00</td>
</tr>
<tr>
<td>- long-term</td>
<td>1,0</td>
<td>0,20</td>
<td>0,00</td>
</tr>
<tr>
<td><strong>Natural Gas</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>0,03</td>
<td>0,34</td>
<td>0,00</td>
</tr>
<tr>
<td>- medium-term</td>
<td>0,01</td>
<td>0,10</td>
<td>0,00</td>
</tr>
<tr>
<td>- long-term</td>
<td>0,01</td>
<td>0,10</td>
<td>0,00</td>
</tr>
<tr>
<td><strong>Hydrogen</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
<tr>
<td>- medium-term</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
<tr>
<td>- long-term</td>
<td>0,00</td>
<td>0,00</td>
<td>0,00</td>
</tr>
</tbody>
</table>

Tab. 5.1: Expected Level of Emission in a short, medium and long-term View (Vans; Source: Ludwig-Bölkow-Systemtechnik GmbH, 1996)
As the above figure illustrates, the aim of a zero-emission standard in the transport sector can only be fulfilled through the use of a hydrogen propulsion system, provided that this system is based on the fuel cell technology instead of using combustion engines. Water and water vapor are the only expected by-products of the fuel cell system. Due to the "zero emission" standard, the fuel cell technology can meet the strictest air pollution standards in the future. In contrast to hydrogen and natural gas, the emission standard of diesel and gasoline will still be high, despite the improvement of the combustion engine system, the use of low benzol gasoline, low sulfur diesel and catalytic converters.

5.1.2 Energy Efficiency

In addition to the emission standard, energy efficiency is also a very important key variable in evaluating the hydrogen propulsion system and its competitors in terms of environmental impacts. The energy efficiency describes the relationship between the provision of one desired service unit and the total energy consumption which is needed to produce it; For example, the service of 1 km of travel in the transport sector (Schmidt-Bleek, 1994). The following table shows a comparison of the expected energy efficiency in the future between the hydrogen propulsion system and its competitors.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydro Power</td>
<td>95-98 %</td>
<td>99 %</td>
<td>97 %</td>
<td>97 %</td>
</tr>
<tr>
<td>Electrolysis</td>
<td>90 %</td>
<td>90 %</td>
<td>79 %</td>
<td>90 %</td>
</tr>
<tr>
<td>Compression</td>
<td>82 %</td>
<td>50 %</td>
<td>82 %</td>
<td>Transport</td>
</tr>
<tr>
<td>Transport</td>
<td>94 %</td>
<td>94 %</td>
<td>94 %</td>
<td>Fuel Cell Techn.</td>
</tr>
<tr>
<td>Fuel Cell Techn.</td>
<td>40 %</td>
<td>40 %</td>
<td>40 %</td>
<td>= 26,9 %</td>
</tr>
<tr>
<td>Provision of Natural Gas</td>
<td>97 %</td>
<td>79 %</td>
<td>75 %</td>
<td>90 %</td>
</tr>
<tr>
<td>Steam Reforming</td>
<td>90 %</td>
<td>90 %</td>
<td>82 %</td>
<td>Transport</td>
</tr>
<tr>
<td>Compression</td>
<td>94 %</td>
<td>94 %</td>
<td>94 %</td>
<td>Fuel Cell Techn.</td>
</tr>
<tr>
<td>Transport</td>
<td>40 %</td>
<td>40 %</td>
<td>40 %</td>
<td>= 25,9 %</td>
</tr>
<tr>
<td>Fuel Cell Techn.</td>
<td>= 26,9 %</td>
<td>= 25,9 %</td>
<td>= 22,2 %</td>
<td></td>
</tr>
<tr>
<td>Provision of Biomass</td>
<td>96 %</td>
<td>75 %</td>
<td>82 %</td>
<td>94 %</td>
</tr>
<tr>
<td>Gasification</td>
<td>90 %</td>
<td>90 %</td>
<td>94 %</td>
<td>40 %</td>
</tr>
<tr>
<td>Compression</td>
<td>94 %</td>
<td>94 %</td>
<td>94 %</td>
<td>Fuel Cell Techn.</td>
</tr>
<tr>
<td>Transport</td>
<td>80 %</td>
<td>80 %</td>
<td>80 %</td>
<td>= 26 %</td>
</tr>
<tr>
<td>Fuel Cell Techn.</td>
<td>= 26 %</td>
<td>= 26 %</td>
<td>= 26 %</td>
<td></td>
</tr>
<tr>
<td>Provision of Gasoline</td>
<td>97 %</td>
<td>90 %</td>
<td>90 %</td>
<td>90 %</td>
</tr>
<tr>
<td>Refining Process</td>
<td>94 %</td>
<td>94 %</td>
<td>94 %</td>
<td>Transport</td>
</tr>
<tr>
<td>Transport</td>
<td>80 %</td>
<td>80 %</td>
<td>80 %</td>
<td>POX-Reformer</td>
</tr>
<tr>
<td>Fuel Cell Techn.</td>
<td>= 40 %</td>
<td>= 40 %</td>
<td>= 40 %</td>
<td>Fuel Cell Techn.</td>
</tr>
<tr>
<td>= 26 %</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

|                                               | 97 %                     | 97 %                 | 99 %       | 90 %         | 82 %        | 94 %      | = 25 %           |
| Provision of Natural Gas                      | 90 %                     | 90 %                 | 90 %       | 90 %         | 82 %        | 94 %      | = 25 %           |
| Steam Reforming                               | 90 %                     | 90 %                 | 90 %       | 90 %         | 82 %        | 94 %      | = 25 %           |
| Compression                                   | 94 %                     | 94 %                 | 94 %       | 94 %         | 94 %        | 94 %      | = 25 %           |
| Transport                                     | 25 %                     | 25 %                 | 25 %       | 25 %         | 25 %        | 25 %      | = 25 %           |
| Fuel Cell Techn.                              | = 20,5 %                 | = 20,5 %             | = 17,2 %   | = 20,5 %     | = 20,5 %   | = 20,5 % |

1) Achievable energy efficiency of a high-pressure electrolysis in the future (Dechena, adopted from Grubel, 1996)
2) Energy efficiency of gasification (Wagner et al., 1996)

Tab. 5.2: Energy Efficiency of the Hydrogen Propulsion System and its Competitors (Source: Mainly adopted from the Department of the Environment (Umweltbundesamt, 1999)
Accordingly, the hydrogen propulsion system could provide huge potentials in the future to reduce the total energy intensity of the transport sector and its impacts on the environment, mainly due to the significantly higher energy conversion efficiency of the fuel cell technology compared to internal combustion engines. Especially during the operating phase, which is characterized by a large amount of partial load, the energy efficiency of the fuel cell technology is much higher than that of its competitors. This advantage is very important considering the stop-and-go driving cycle in the road traffic system of large cities and the driving-cycle of city-buses (mainly short distances between stops; stop-and-go in towns). The higher energy efficiency of the hydrogen propulsion system can be destroyed by using liquid hydrogen. Presently, the liquefaction of hydrogen is very energy intensive. This situation can be improved through a further development of the process in the medium and long-term view.

5.1.3 Material-Use

In addition to the material and energy intensity, the use of fossil fuels and non-renewable materials must be avoided due to both the ongoing depletion of limited fossil fuels and the concept of Sustainable Development. A sustainable material-use implies that the "consumption of a resource may not exceed its regeneration rate or the rate at which all its functions can be substituted" (Umweltbundesamt, 1997).

Material-Use during the Usage

A sustainable energy use in the transport sector can only be achieved through the use of renewable energy resources like biomass, wind, hydro and solar power. In contrast, the replacement of oil with natural gas cannot solve the problem of the limitation of fossil fuels in a long-term view because natural gas is a limited fossil fuel as well: "The more we try to replace oil with gas, the sooner this will turn out to come to a limit. The supply of natural gas and mineral oil will then end at about the same time" (Schindler/Zittel, 1999).

Material-Use during the entire Generation and Distribution Process

One drawback of the fuel cell technology is the need for platinum. The total world supply of platinum is limited, and the precious material is in demand for many other uses as well. According to Appleby, the production of two million fuel cell cars (which amounts 2% of the current world vehicle production), each powered by a 50 kW PEM engine, would require 50 metric tons of platinum, about one 1/3 of the current world production of platinum. Therefore he concludes that pure proton-exchange membrane fuel cell vehicles will not dominate the future world market caused by the scarcity of platinum which will result in higher prices (Fuel Cell Letter, July 1999). Therefore, a further development of fuel cell technologies is required in order to reduce or to prevent the use of expensive and rare catalytic material like platinum.

5.2 Obstacles

In general, through the use of hydrogen propulsion systems in the transport sector, the major global and local environmental problems could be minimized, because all kind of emissions could be avoided during the usage. In addition, compared to internal combustion engines, hydrogen propulsion systems based on renewable energy resources would lead to a higher energy efficiency over the entire lifecycle of the product. The liquefaction process cannot be recommended due to the higher energy and material consumption during the utilization process. According to above described analysis, the drawbacks of hydrogen propulsion systems are the low state of technology and the lack of knowledge of society about the environmental advantages of hydrogen propulsion systems (Ludwig-Bölkow-Systemtechnik GmbH, 1997 a).
6. Legal Requirements

6.1 Analysis of the Environmental Policy Making Process

In this section, the environmental policy making process is analyzed in order to assess the further development of legal requirements in the field of road traffic. The following causal loop diagram illustrates the complexity of the process. It shows the main players of the policy making arena, their interests, opinions and priorities.

![Causal Loop Diagram](image)

In general, the environmental policy making process can be influenced by different actors like industry, mass-media, civic action groups, environmental groups and associations. All mentioned groups have in common the ability to exercise influence on society, especially on voters as the main target group of the German government (Hempel, 1996). Due to the short election period (4 years), the present day-to-day practice of politicians is often driven by short-term goals in order to satisfy the voters and to ensure their re-election. In some cases, these circumstances and dependencies prevent a rational, sustainable-oriented policy. These interrelations are illustrated in figure 6.1 through negative feedback loops which are described in the following sections. The negative feedback loops describe constraints on the environmental policy, including conflicting aims, the involvement of several actors, their different interests and the scarcity of financial resources. As shown in figure 6.1, the negative feedback loops will affect the balancing loop in the following manner: an increase of environmental pollution will lead to an increasing demand for an environmental policy. The demand for environmental policy will cause a change in the policy system towards a more environmental-friendly system, which could reduce the environmental problems to some extent resulting in a decrease in demand for additional environmental policy and so on.

6.2 Environmental Policy in the Transport Sector

6.2.1 Internalization of external Costs

The internalization of the external costs on products and services through the establishment of new taxes and fees is a powerful strategy to reduce the impacts on the environment. This strategy is being used by the German government, which consists of the "Social Democratic..."
Party (SPD) and the "Green Party" (Bündnis 90/Die Grünen), through the creation of a "green tax" on electricity and mineral oil (see figure A.IV.2; Bundesregierung der Bundesrepublik Deutschland, 1999). In addition, the German government established further economic incentives for using environmentally-sound technologies in the transport sector. Some of such incentives are the "Motor Vehicle Tax" and the tax on mineral oil. A major constraint on the strategy can be explained through the following balancing loop: New tax and fee initiatives will increase the costs to the consumer resulting in a decrease in the demand for more environmental policy. This interrelation describes the discrepancy between environmental awareness and environmental behavior, which means that everybody is asking for more environmental policy but nobody wants to pay for it. The outcome of this interrelation is a reduction or minimization of legal activities. Example: The recent termination of the discussion about the need for an increase in tax on diesel by German chancellor Schröder in the last week of August, and the ongoing discussion about the basic idea of the green tax are two examples for the negative feedback loops.

**Expected Trend in the Future**
The governmental decision to increase the green tax on mineral oil annually by 6 German Pfennig in the next four years is one example of the government’s willingness to change but it is also a sign of their limitations, caused by the power of both the lobby and the voter. Therefore, a further significant increase in the green tax cannot be expected in the future. This assumption is only truer in the case of a possible change of government in the year 2002. The current opposition does not support the concept of the "green tax" at all.

**6.2.2 Environmental Regulations and Agreements**
In order to ensure the fulfillment of the societal-driven requirements, the German government put a bundle of different regulations and legislation (e.g. "Motor Vehicle Construction and Use Regulations" and "Law of Emission Protection") into operation regarding the production, use and disposal of vehicles and fuels. The establishment of new national regulations in the transport sector is restricted by international agreements and organizations like the "World Trade Organisation" (WTO) and the "European Union" (EU; Hempel, 1996). Furthermore, national regulations can be avoided by lobbyists. These interrelation can be explained through the following balancing loop (see figure 6.1): the establishment of new regulations could increase the costs to both the consumer and the industry resulting in a decrease of the competitive power of the national industry in the global market. The outcome could be the formation of blocking coalitions and a decrease in the voter demand for more environmental policy. Example: The blockade of the German government against the EU-legislation on the obligation for car-manufacturers to recycle used vehicles (Bundesumweltministerium, 1999) is one example for the aforementioned balancing loop. This decision of the German government was based on consideration for the car-manufacturers in Germany.

International agreements enable some of the previously mentioned constraints to be managed, such as disadvantages for the industry caused by the establishment of national regulations. International agreements will lead to comparable environmental standards resulting in an equal legal framework for involved companies. This could lead to an increase in competitive power for German industry due to the higher environmental knowledge at present in comparison to other states. Therefore, the establishment of more international agreements in the future are desired by the main market players. But there are several constraints for international agreements. It is much more difficult and time-consuming due to the increased number of involved actors and their different interests. Nevertheless, the number of international agreements will significantly increase in the future in order to solve the
transboundary environmental problems and to overcome the obstacles of a purely national "go-it-alone-approach".

**Expected Trend in the Future**

Due to the expected increase of both road traffic and the level of degradation of the ecological environment worldwide, further political activities on a global level (binding and non-binding international agreements) can be expected. However, due to both the time-consuming negotiation process of international conventions and the different interests of participating states, these activities will not lead to a break-through in environmental policy in the field of road traffic in a short or medium-term. Therefore, only small improvements in international environmental legislation will take place in the short and medium-term causing a marginal impact on the current structure of road traffic.

6.2.3 Economic Incentives and Awareness Programs

Economic incentives like subsidies and promotion activities encourage the industry to invest in the development of environmentally-sound technologies. The aim of these measures is to support the market penetration of new environmentally-sound technologies and to strengthen the competitive power of the national economy. Accordingly, these measures are offering a chance for a new market for companies instead of determining new regulations. Therefore, the industries are greeting such kinds of measures and asking for more support (reinforcing loop shown in figure 6.1). Nevertheless, the establishment of new economic incentives is dependent on and restricted by the financial power of the government. For this reason, the government has to negotiate trade-offs between the conflicting aims of supporting new technologies and reducing the costs to society. Therefore, the further support of hydrogen propulsion systems by the German government (through economical incentives) in the future is depending on a costs-benefit analysis. The same interrelations can be expected for the implementation of environmental awareness programs that aim at a change in both consumption behavior and customer requirements. Example: A costs-benefit analysis was carried out by the department of the environment (Umweltbundesamt, 1999) in order to inform the government about alternative technologies and their costs and benefits. Accordingly, the further support of the hydrogen propulsion system is not recommended by the department due to the low degree of technological ripeness, including the higher costs in comparison with alternative technologies (e.g. low sulfur diesel).

**Expected Trend in the Future**

According to the above mentioned arguments, a further significant increase in support activities, including economic incentives for the hydrogen propulsion system, cannot be expected in the short or medium-term.

6.3 Evaluation of the Hydrogen Propulsion System

Due to both the environmental improvements of the conventional propulsion systems in the future (for instance through the production of low benzol gasoline or low-sulfur-diesel and the use of catalytic converters) and the low level of legal requirements in the field of road traffic, all kinds of propulsion systems can fulfill the legal requirements in a short and medium-term. Therefore, only the performance of the different propulsion systems with respect to the customer requirements and the financial support of the government will be decisive for the success of the hydrogen propulsion system on the market in a short and medium-term. On the contrary, the hydrogen propulsion system could have advantages in a long-term view provided that the German government introduces new regulations that aim at the creation of sustainable road traffic (e.g. the determination of a zero-emission standard).
The exact date of this event are uncertain and speculative at this moment. But it can be expected that it will take a long time as a result of the slow and time-consuming policy making process including lobby activities of blocking coalition groups.

6.4 Obstacles – Legal Requirements
The following obstacles for the implementation of hydrogen can be expected:

- the present day-to-day practice of politicians driven by *short-term goals* in order to satisfy voters and to ensure re-election;
- the *dependency* of the government on goals declared and established by the powerful (e.g. car manufacturers and oil companies) according to their interests, values, or whims.
- the use of a *cost-effectiveness analysis* to select alternatives with the lowest monetary cost; that is, those that represents the best "value for money";
- the *lack of a comprehensive cost calculation* which includes all expenses of the road traffic including external costs like the degradation of the environment;
- the *conflicting aims* of the government resulting in a *low priority* of environmental issues; for instance, the government is trying to reduce both local (priority B) and global emissions (priority C) and the use of non-renewable energy sources (priority D) in the transport sector in a short-term view without affecting the competitiveness of the German industry (priority A);
- the *restriction of national "go-it-alone" approaches* by international agreements;
- the *time consuming negotiation process* of international agreements;
- the *discrepancy between environmental awareness and behavior* of society;
- the need for using hydrogen based on fossil fuels as a *temporary solution* which would lead to an increase in environmental problems on a global scale. This disadvantage could increase the risk for the German government that their society will not accept their policy.

7. Customer Requirements

7.1 Description of the Customer Requirements
The customer requirements were mainly investigated through interviews with the companies "Hermes Versand Service" and "Hamburger Hochbahn AG". The companies were asked to define their own customer requirements with respect to the desired driving performance of the present and future state of vehicles technology. The requirements for passenger cars were defined through both a literature review and an analysis of the public statistics of road traffic in Germany. The public statistics are investigated and maintained by the state-owned office "Kraftfahrt-Bundesamt". The customer requirements are described in table A.IV.5. In general, this are mainly low life-cycle costs and the fulfillment of legal technical and environmental requirements. The more specific requirements are described in the following section in terms of the three different case-studies.

*Case-Study: City-Buses*
The requirements of the customer (mainly public transportation companies) regarding the driving performance of city-buses are dependent on the driving cycle. The driving cycle of city-buses is characterized by mainly short distances between stops and stop-and-go in towns. A range of at least 300 km per day and 500 km per "fill-up" is required in order to stand the daily driving conditions and to reduce the variable costs of refueling services. The refueling services should be quick and convenient to the user. The refueling-time should not exceed 4-5 minutes. In addition, the shape of the vehicle should be characterized by both a high carrying capacity (70-100 persons with at least 30 seats) and a steep- and pedestal-free ground (low-
flour concept) in order to provide a high access comfort, for instance, for handicapped and old people. Furthermore, a sufficient power supply in all kinds of operation-phases is desired by the bus-fleet operators in order to ensure any desired service to the customer, for example information services, entertainment services (television), supply of heating and air-conditioning systems and business services (sale of drinks; Behrmann, 1999 a and b).

**Case-Study: Vans**
The driving cycle of vans is characterized by mainly long distances between stops, stop-and-go in towns and high speed on highways. Therefore, a high acceleration, a top speed of 130 km/h and a range of 200 km per day and 600 - 700 km per "fill-up" are required. The company "Hermes Versand Service" is not interested in operating their own fuel station at the depots. Therefore, a high availability of convenient and quick refueling services are needed. The refueling-time should not exceed 4-5 minutes. The shape of the vehicle should be characterized by a square shape of the loading space, a high load carrying capacity (volume) and a low total vehicle weight. The provision of a leasing and maintenance contract is a further requirement of the Hermes Versand Service in order to be up-to-date with the newest state of technology (Schuldt, 1999).

**Case-Study: Passenger Cars**
In the case of "Passenger Cars" a high acceleration, a top speed of 180-200 km/h, a high power of the propulsion system and a range of around 650 to 800 km per "fill-up" are required. In addition, a wide-spread service-infrastructure with respect to refueling and repair services is needed. The refueling service should be convenient and based on do-it-yourself stations. The refueling time should not exceed 5 minutes. A sufficient supply of power for different purposes in all kind of operation-phases (especially, during the stop of the vehicle) is also important. This would make it possible to provide new services like air conditioning and entertainment services. In addition, already achieved safety standards such as air bags, and comfort standards such as low noise emission have to be at least met if not exceeded.

### 7.2 Evaluation of the Hydrogen Propulsion System
There are a few difficulties to overcome before a widespread market penetration of the hydrogen propulsion system is likely. These difficulties (obstacles) are described in the following section in terms of the following customer requirements:

- Technology,
- Service-Infrastructure,
- Life-Cycle Costs,
- Availability and
- Acceptance.

#### 7.2.1 Technology
In general, the onboard hydrogen storage system does not involve more serious safety problems than the structure currently in place with gasoline, but it needs to be handled differently. In the case of enclosed areas, sensors can be installed to detect concentrations of hydrogen approaching 4 % - the lowest point at which ignition can occur – in which case safety systems can be brought into operation (IEA Greenhouse Gas R & D Programme, 1999). The more specific obstacles of the hydrogen propulsion system are described in the following section with respect to the three different case-studies.
Case Study "City Buses"

<table>
<thead>
<tr>
<th>Fulfillment of the customer requirements</th>
<th>Requirements/Performance of Diesel Powered Buses</th>
<th>MAN (liquid hydrogen)</th>
<th>Daimler/Chrysler (gaseous hydrogen)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving range:</td>
<td>300 - 350 km per day and around 500 per &quot;fill up&quot;</td>
<td>250 km per &quot;fill up&quot;</td>
<td>250 km per &quot;fill up&quot;</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Top speed</td>
<td>80 km/h</td>
<td>80 km/h</td>
<td>80 km/h</td>
</tr>
<tr>
<td>Horsepower</td>
<td>231-354 PS / 170-260 kW</td>
<td>204 PS 150 kW</td>
<td>no data available 250 kW</td>
</tr>
<tr>
<td>Electric Power</td>
<td>reliable/trouble-free/calm</td>
<td>unknown - yet</td>
<td>unknown - yet</td>
</tr>
<tr>
<td>Driveability</td>
<td>average bus with two doors: 106 persons (Standing-places: 68; Seats: 38)</td>
<td>no data available</td>
<td>58 passenger (Seats: 34; Standing-places: 24)</td>
</tr>
<tr>
<td>Load carrying capacity:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shape of vehicle</td>
<td>Low-flour-concept</td>
<td>Low-flour-concept</td>
<td>Low-flour-concept</td>
</tr>
<tr>
<td>Safety</td>
<td>High standard</td>
<td>Comparable to diesel</td>
<td>Comparable to diesel</td>
</tr>
<tr>
<td>Design</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tab. 7.1: Fulfillment of the Customer Requirements – Fuel Cell City-Buses - in 1999 (Source: MAN, 1999; DaimlerChrysler 1999 c). Liquid Hydrogen Buses are not considered in this analysis because of their lower energy efficiency and higher level of emissions compared to fuel cell buses based on gaseous hydrogen (see chapter 5). The previously mentioned fuel cell buses are shown in section A.III.

At present, the hydrogen propulsion system cannot compete with diesel and natural gas due to the unknown driving performance under real day-to-day driving conditions and worse performance in specific power compared to diesel. The restricted range cannot be seen as a constraints because a range of 250 km is sufficient for urban scheduled services. In addition, the lack of a wide-spread service-infrastructure can be managed through a depot refueling of urban bus fleets. An advantage of the fuel cell technology is the sufficient power supply. Currently, all kinds of conventional city-buses suffer from an insufficient power supply. The need for power can only be met through additional activities like the refilling of the battery at the bus-depot. This unsatisfactory situation can be changed through the use of the fuel cell technology. This advantage of the fuel cell technology is very important for providing of new desired on-board services to the customer such as information services, entertainment services (television), and the supply of heating and air-conditioning systems and business services (sale of drinks). This would increase the level of customer satisfaction and the attractiveness of the public transport. The consequence could be an increase in the number of customers (Behrmann, 1999 a and b). In a medium-term view, it can be expected that fuel cell buses will fulfill the driving performance in the same manner as diesel powered buses due to the further development of the technology.

Case Study "Passenger Cars"

The difficulties of storing sufficient H2 on board a vehicle is one major obstacle. The on-board storage of the fuel (currently mainly done with liquid hydrogen) determines the range of the vehicle. A range of about 450 km per "fill up" is still too short and therefore not competitive with conventional fuels. Presently, the use of gaseous hydrogen can be neglected in the field of passenger cars due to the much lower driving range of the vehicle (e.g. the driving range of the GH2-powered NeCar II of DaimlerBenz amounts about 250 km) caused by the low volumetric energy density of gaseous hydrogen in comparison to liquid fuels. The unknown driving performance under real day-to-day driving conditions and the worse performances in specific power of the fuel cell technology are further constraints on the technology.

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>BMW 7-Series (LH2; combustion engine)</th>
<th>BMW 7-Series (LH2; combustion engine)</th>
<th>Daimler/Chrysler A-class</th>
<th>Daimler/Chrysler (Necar IV: A-class: LH2 fuel cell car)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving range</td>
<td>650-800 km per &quot;fill up&quot;</td>
<td>300-400 km per &quot;fill up&quot;</td>
<td>650-800 km/ &quot;fill up&quot;</td>
<td>450 km per &quot;fill up&quot;</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Top speed</td>
<td>243 km/h</td>
<td>170 km/h</td>
<td>170 km/h</td>
<td>145 km/h</td>
</tr>
<tr>
<td>- Power:</td>
<td>max. 142 – 175 kW</td>
<td>max. 80 kW</td>
<td>82 kW</td>
<td>55 kW (electric-motor); 70 kW (twin-stack PEM fuel cell)</td>
</tr>
<tr>
<td>- Driveability</td>
<td>unknown - yet</td>
<td>unknown - yet</td>
<td>reliable/trouble-free/calm</td>
<td>unknown - yet</td>
</tr>
<tr>
<td>- Safety</td>
<td>High standard</td>
<td>Comparable to its competitor</td>
<td>High standard</td>
<td>Comparable to its competitor</td>
</tr>
</tbody>
</table>


### Case Study “Vans”

<table>
<thead>
<tr>
<th>Customer Requirements</th>
<th>Mercedes Benz Sprinter</th>
<th>Mercedes Benz GH2-Sprinter (combustion engine)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving range</td>
<td>200 km per day and 600-700 km per &quot;fill up&quot;</td>
<td>600-700 km per &quot;fill up&quot;</td>
</tr>
<tr>
<td>Performance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Top speed</td>
<td>135 km/h</td>
<td>135 km/h</td>
</tr>
<tr>
<td>- Power:</td>
<td>58 kW</td>
<td>58 kW</td>
</tr>
<tr>
<td>- Driveability</td>
<td>reliable/trouble-free/calm</td>
<td>reliable/trouble-free/calm</td>
</tr>
<tr>
<td>Load carrying capacity</td>
<td>800 kg / 10,5 m³; Trend of the next decade: increase of the load carrying capacity and decrease of the total weight of empty vans</td>
<td>800 kg / 10,5 m³</td>
</tr>
</tbody>
</table>


The driving performance of fuel cell vans is unknown because the technology is still in the prototype phase. Therefore, the table above shows the technical performance of a hydrogen powered combustion engine. The vehicle is a part of W.E.I.T. demonstration project in Hamburg. As the table shows, a hydrogen powered van cannot compete with the conventional propulsion system in a short-term view due to the lower driving range and the lower load carrying capacity, which is very important for the user. In addition, the required day-to-day driving condition cannot currently be met. Due to further improvements in fuel cell technology based on experiences in the field of "City Buses" and "Passenger Cars", it can be expected that fuel cell vans will be able to fulfill the customer requirements in a medium-term. For instance, the load carrying capacity can be increased by putting the storage tanks of compressed hydrogen on the roof of the vehicle.

### 7.2.2 Service-Infrastructure

In general, it has not yet been proven if the customer requirements on the service-infrastructure (like refueling convenience or refueling time) can be achieved in a short-term due to the lack of experiences in day-to-day practice caused by the fact that hydrogen based refueling stations are still in the demonstration and prototype phase.
Case Study "Passenger Cars"
One of the most important barriers to the market introduction/penetration of hydrogen-fueled passenger cars is the lack of a supporting infrastructure. At present, there are only a couple of locations in Germany (one in Hamburg – gaseous hydrogen – and one in Munich – liquid hydrogen) where hydrogen vehicles can be refueled. The availability of hydrogen is an important factor in determining its acceptability. There is no willingness from the customers to change their vehicles if they can only refuel their cars at one or two specialized sites. Hydrogen must be available at a significant number of service stations (IEA Greenhouse Gas R&D Programme, 1999). The implementation of a wide-spread refueling infrastructure should not be limited to Germany, it must also be possible for users to refuel their cars in most other countries in Europe, e.g. during the vacation.

Case Studies "City Buses and Vans"
The restricted range and the depot refueling of urban bus and vehicles fleets enable some of the above mentioned constraints to be managed. Buses and vans can carry tanks of compressed hydrogen on the roofs without affecting both the carrying capacity and its performance.

7.2.3 Life-cycle Cost
The life-cycle cost of the hydrogen propulsion system is very important for the implementation of the fuel cell technology. It will mainly determine the success of the technology on the market. In the following sections, the costs of both the fuel and the fuel cell technology are estimated and compared with the costs of its competitors (diesel, natural gas and gasoline).

7.2.3.1 Cost of the Fuel Cell Technology
Case-study: City-Buses (Hamburger Hochbahn AG)
Daimler-Benz estimates the costs of the first prototype bus at about DM 2 million by the year 1999. Within the next six years, Daimler-Benz foresees a reduction by 60 % (market price of about DM 800,000) by the time period 2002-2003 and by around 70 % (market price of about DM 550,000) by the year 2005 (Ebner, 1998; Hydrogen & Fuel Cell Letter, June 1997). This equivalent to the market price of natural gas and DM 50,000 higher than diesel at present. According to Mister Schaller (MAN Utility Vehicle AG), the view of Daimler-Benz is too optimistic. On the contrary to Daimler-Benz, he estimates the costs of a fuel cell bus at about DM 2-3 million by the year 2002. Furthermore, a market price of about DM 550,000 can be achieved by the year 2010 at the earliest (Schaller, 1999).

Case-study: Passenger Cars and Vans (Hermes Versand Service)
The current engine cost per power unit of an automotive fuel cell system amounts around $ 3-4,000 per kW (Schaller, 1999). Most of the PEMFC companies (e.g. De Nora, H Power, Siemens, Daimler-Benz) seem to agree that PEMFC system costs for fully integrated hydrogen fueled systems of US$ 1,000 can be reached within the next two years (Ludwig-Bölkow-Systemtechnik GmbH, 1999 b). According to Ballard, the costs for the propulsion system are likely to drop further to 40 USD/kW at a 100,000 units per year production level in a long-term view (Kalhammer et al., 1998). For the methanol powered fuel cell vehicles, the costs are estimated to be slightly higher (45 USD/kW), because of the increased complexity due to the methanol reformer (Jung, 1999). Currently, the costs for an internal combustion engine are estimated to amount around 30-50 USD/kW (Hart et al., 1998). The additional costs of the fuel cell technology are summarized in the following table for the three
different time-scales in order to take into consideration the different states of technology in a short (0-5 years away), medium (5-10 years away) and long-term view (10 and more years away). To simplify the calculation, the costs of the internal combustion engine are assumed to be fixed.

| Tab. 7.4: Estimated costs of the Fuel Cell Technology in short, medium and long-term View |
|---------------------------------|---------------------------------|---------------------------------|
| Passenger Car                   | Current Situation   | Short/Medium-Term View   | Long-Term View   |
| 59 kW                           | 175.230 USD         | 57.230 USD               | 590 USD          |
| 74 kW                           | 220.230 USD         | 71.780 USD               | 740 USD          |
| Vans                            | 172.260 USD         | 56.260 USD               | 580 USD          |
| 58 kW                           | 504.900 USD         | 164.900 USD              | 1.700 USD        |
| City Bus                        | 772.200 USD         | 252.200 USD              | 2.600 USD        |

### 7.2.3.2 Fuel Cost

The total fuel costs consist of production, transportation, distribution and utilization expenses. In addition, the profit of the producer, distributor and trader and taxes are also included, which are dependent on both the current market situation and the political framework. Due to the uncertainty of the development of the market situation in the future, the profit of the market players are not considered in the following calculation.

#### Production Cost

The production cost of hydrogen can be estimated in the following (Zittel/Wurster, 1999; the calculation is based on an assumption of a production capacity of 110,000 Nm3/h; 1 Pf/kWh ≈ 10 Pf/l equivalent to diesel.):

- Petrochemical processing (steam reforming):
  - Hydrogen based on natural gas: 4.6 Pf/kWh
- Gasification:
  - Hydrogen based on coal (according to Winkler): 7.8 Pf/kWh
  - Hydrogen based on coal (according to Koppers/Totzek): 12.2 Pf/kWh
  - Hydrogen based on biomass: 10.0 Pf/kWh
- Partial oxidation:
  - Hydrogen based on crude oil: 5.9 Pf/kWh
- Electrolysis:
  - Hydrogen based on hydro power: 5 - 10 Pf/kWh
  - Hydrogen based on wind power: 15 - 30 Pf/kWh
  - Hydrogen based on solar-thermal power plants: 30 - 40 Pf/kWh
  - Hydrogen based on solar power (photovoltaic plant in Africa): 400 Pf/kWh
- Hydrogen based on chemical surplus production: 31 Pf/kWh

The production of hydrogen is basically linked to the electricity market. Due to the liberalization of the electricity market in Europe, which resulted in a decrease of the electricity price, a further reduction of the production costs of hydrogen can be expected in a short-term view. The following production costs of hydrogen based on renewable energy sources can be achieved through further development of the technologies in a long-term view (Zittel/Wurster, 1999):

- Hydrogen based on biomass: 8 Pf/kWh
- Hydrogen based on wind power: 8 - 12 Pf/kWh
- Hydrogen based on solar-thermal power plants: 15 - 20 Pf/kWh
- Hydrogen based on solar power (photovoltaic): 22 Pf/kWh
On site production of hydrogen via small scale reforming of natural gas or electrolysis can be economically attractive because of the advantage that no hydrogen distribution system is required provided it is based on larger station sizes (Ogden, 1999).

**Cost of Transport and Distribution**
The cost for various transport and distribution systems can be expected in the following:

- The costs of a maritime transport of liquid hydrogen based on hydro power from Canada to Germany (Hamburg) will amount to around 11, 5 Pf/kWh including the distribution costs. The total cost of hydrogen is expected to amount to 31 Pf/kWh. The total cost situation can be improved through the use of new developed transport containers. In this case, the costs would amount up to 18 - 20 Pf/kWh, 8 Pf/kWh of which are transport cost alone (EQHHPP adopted from Zittel/Wurster, 1999).
- The costs of both the maritime transport and the further distribution of liquid hydrogen from Norway to the end-user in Germany will amount around 18 - 20 Pf/kWh, 8 Pf/kWh of which are transport cost alone (NHEG adopted from Zittel/Wurster, 1999).
- The costs of a maritime transport of gaseous hydrogen based on hydro power from Island to Germany (Hamburg) will amount around 4 Pf/kWh including the distribution costs. The total cost of hydrogen is expected to amount 13 Pf/kWh (EQHHPP adopted from Zittel/Wurster, 1999).
- Pipeline hydrogen could offer low transport and delivery costs under certain conditions. The capital costs of building a small (3 in diameter) hydrogen pipeline would be about $ 1 million per mile. The total distribution costs are dependent on both the pipeline length (mile/km) and the hydrogen flow-rate. The higher the flow rate, and the shorter the pipeline, the lower the cost. According to a Southern California case study carried out by Ogden (1999) the transmission cost of about $ 1/GJ would allow a pipeline distance of about 10 km in the heavily populated Los Angeles area provided that the flow rate amounts about 10 million scf/day (an amount which could serve a total fleet of 92,000 cars).
- The distribution costs of truck delivered liquid hydrogen amounts to around $ 20-30/GJ, dependent on the station size and the distance (Ogden, 1999).

**Utilization Cost**
The costs of liquefaction of hydrogen can be expected to amount about 13 - 15 Pf/kWh for a small-scale production and about 9,3 Pf/kWh for a large-scale production (capacity: 74 MW). This cost situation can be reduced by 30 % through improvements of the technology in the future (EQHHPP adopted from Zittel/Wurster, 1999).

The compression of hydrogen can be expected to be three times more expensive than the compression of natural gas due to the different energy content. The costs of compressing gaseous hydrogen amounts around 10 to 20 Pf per Nm³ dependent on the size of the compression/filling station (Zittel/Wurster, 1999).

**Calculation of the total Fuel Cost of Hydrogen**
The total fuel cost of hydrogen is summarized in table 7.5. The table shows an estimation of the total fuel cost of hydrogen (total cost from well to wheel) in relation to the three different production possibilities in a medium-term. The shown calculation includes the entire production process of hydrogen and the different energy efficiencies of both the fuel cell technology and the conventional combustion engine.
Accordingly, the hydrogen propulsion system cannot compete with the conventional fuels despite a higher energy efficiency. The production costs are still too high. As of yet, it is still uncertain whether or not, and to what extent the German government will put taxes on hydrogen. The table A.IV.6 shows two different scenarios: a best-case scenario (no taxes on hydrogen) and a worst-case scenario (100% taxes on hydrogen).

In addition, the cost of developing a hydrogen infrastructure with distribution and refueling stations is a further major constrain regarding the market penetration of the fuel cell technology in Germany. According to Ogden (1999), the range of infrastructure capital costs for a system serving 18,400 fuel cell cars is about $1.4 - 11.4 million or $80 - 620 per vehicle.

### 7.2.4 Availability

#### 7.2.4.1 Availability of Hydrogen

The availability of hydrogen is dependent on both the production capacity and the infrastructure of the refueling system including the distribution of hydrogen. In the near future, the total demand for hydrogen cannot only be met through the use of renewable energy sources like wind, solar and hydro power because of their higher production costs and the limited production capacity at present. This situation can be changed in the medium and long-term through the further development of the relevant technologies supported by the environmental policy of the government. Accordingly, the use of hydrogen based on fossil fuels as a temporary solution is necessary in order to ensure the market penetration of fuel cell technology in the short-term view and to enable a continuous transition from the conventional fuels currently in use towards a more sustainable transport system based on renewable energy sources in the future. In this case, the use of hydrogen based on fossil fuels could be the ideal starter for the introduction of the fuel cell technology on the market in the
short-term and for paving the way for renewable sources in the transport sector in the medium and long-term. Therefore, the following several concepts, which are feasible in principle for the introduction of the hydrogen propulsion system in the transport sector on a larger scale, have to be considered (Bünger/Schindler, 1998; Wurster, 1997; Ogden, 1999):

**Availability of hydrogen in a short-term view:**

- The use of gaseous hydrogen as a by-product from refineries, electrolytic production (mostly from hydro power) or from other chemical surplus production (mostly chlorine-alkaline-electrolysis).
- On-site hydrogen production at fueling stations for fleet vehicles from natural gas via steam reforming and supply of compressed gaseous hydrogen to the vehicle.
- Refueling of gasoline or diesel at the existing pumps and their onboard partial oxidation to a synthesis gas and to hydrogen.
- Industrial production of methanol from natural gas or from biomass and its onboard reforming process to hydrogen in the vehicle.
- Hydrogen produced from natural gas in a large, centralized steam reforming plant, and truck delivered as a liquid to refueling stations or via small scale hydrogen gas pipeline to refueling stations.
- On-site production at both fueling stations for fleet vehicles and public refueling stations from electricity (based on both renewable and non-renewable energy sources) via electrolysis and supply of compressed gaseous hydrogen to the vehicle.

**Availability of hydrogen in a medium-term:**

- Large-scale production of liquid hydrogen from hydropower (e.g. in Canada or Island), its maritime transport in specially designed containers to the countries of consumption, its distribution there to the refueling station and its supply to the vehicle.
- Large-scale production of hydrogen based on fossil fuels or biomass with sequestering of CO₂.
- On-site hydrogen production at fueling stations for fleet vehicles (e.g. for city-buses of a public transport company) from biomass via gasification and supply of compressed gaseous hydrogen to the vehicle.

**Availability of hydrogen in a long-term:**

- On-site hydrogen production at the public refueling station and at fueling stations for fleet vehicles from electricity based on renewable resources (e.g. wind, solar and hydro power) via electrolysis and supply of compressed gaseous hydrogen to the vehicle.
- Large-scale production of liquid and gaseous hydrogen from wind (from offshore wind parks), solar (for instance, produced in both the Sahelian region and the Middle East) and hydro power (e.g. from Canada and Island), its transport to the countries of consumption through both maritime transport in specially designed containers and via pipelines, its distribution there to the refueling station and its supply to the vehicle.

As the description above shows, the availability of hydrogen cannot be seen as a major constraint, especially in the case of fleet vehicles. There are several technologies to produce hydrogen from a variety of energy sources.
7.2.4.2 Availability of Fuel Cell Vehicles
Currently, the availability of fuel cell vehicles is a major constraint because the fuel cell technology is still in the prototype demonstration phase. According to DaimlerChrysler (Ebner, 1999) and MAN Utility Vehicle AG (Schaller, 1999), the serial production of marketable fuel cell buses can be expected around the time period 2005-2010. Furthermore, it can be expected that fuel cell buses will be the first to penetrate the market followed by fuel cell vans and passenger cars.

7.2.4.3 Willingness to Change and the need for Cooperation
The availability of both hydrogen and the hydrogen propulsion system is also dependent on the major market players’ willingness to change. The major car manufacturers and oil companies are in the following dilemma: on the one hand, oil companies are strongly resistant to change because of the advantages of the oil oligopoly that currently exists. The oligopoly is likely to be broken in the future since hydrogen generation can be done on a much more distributed basis than oil drilling. Therefore, several new market players, like utilities, can enter the market as new competitors resulting in a decrease of market power for the oil companies. Car manufacturers are not willing to change because of the capital sunk, for instance in assembly lines and engine manufacturing plants. On the other hand, both car manufacturers and oil companies have a big interest in providing new technology on the market that can fulfill the legal, customer and societal-driven requirements in the future (Hart, 1997). Furthermore, the investment activities of oil companies are also dependent on the supply of the hydrogen powered vehicles by the car-manufacturers and vice versa. Therefore, cooperative work between the main market players is necessary.

7.2.5 Acceptance
The wide-spread market penetration of hydrogen-powered vehicles is dependent on being accepted by possible customers and society.

Acceptance by the Society
The acceptance by the society is mainly dependent on the level of satisfaction with respect to the societal-driven requirements, which are mainly low emission capability and a high potential for renewable energy sources. Due to the excellent environmental performance of hydrogen, especially in medium and long-term views, a high level of acceptance by the society can be expected provided that it gets sufficient information about the technology through demonstration projects, public relations and environmental education and awareness programs. Until now, the knowledge about the technology has been relatively low (Ludwig-Bölkow-Systemtechnik GmbH, 1997).

Acceptance by the Customer and User
The following level of acceptance can be expected regarding the three case studies:

City Buses: According to a study that was carried out by the Ludwig-Bölkow-Systemtechnik GmbH (1997), the use of the first hydrogen-powered bus in Munich was overwhelmingly greeted by the user. The study shows a relatively high level of acceptance at present, which can be traced back to the fact that the people interviewed saw a high positive relationship between environmental attitudes and the use of the hydrogen propulsion system. The acceptance of the bus operator is mainly dependent on the level of fulfillment of the customer, legal and societal-driven requirements which could be met in the medium-term.
Passenger Cars: Due to the fact that hydrogen powered passenger cars cannot fulfill the customer requirements in the same manner as the conventional technologies, the customer will not accept the new technology in the short and medium-term. Especially, the disadvantages regarding the life-cycle cost and the infrastructure have to be solved in order to increase the level of acceptance.

Vans: Similar to the case study "Passenger Cars", the level of acceptance for hydrogen-powered vans is relatively low mainly due to the higher cost and the lower carrying capacity. In a short and medium-term, the hydrogen powered vans are only of interest for the companies in order to increase the image of the company through public relations. After solving the technical and economical constraints, a high level of acceptance can be expected.

7.3 Obstacles – Customer Requirements
The specific advantages and obstacles of the hydrogen propulsion system compared to those of its competitors are summarized in the following table in terms of the three different case studies. By doing this, the different states of technologies in a short (0-5 years away), medium (5-10 years away) and long-term (more than 10 years away) are also considered.

<table>
<thead>
<tr>
<th>Requirements</th>
<th>Drivng range</th>
<th>Top speed</th>
<th>Durability</th>
<th>Specific Power</th>
<th>Load carrying capacity</th>
<th>Comfort/Safety</th>
<th>Life-cycle costs</th>
<th>Refueling</th>
<th>Refueling convenience and</th>
<th>Availability</th>
<th>Acceptance</th>
<th>Support of the government</th>
<th>on a local scale</th>
<th>Low emissions capability</th>
<th>on a global scale</th>
<th>Environmental Impact</th>
</tr>
</thead>
<tbody>
<tr>
<td>City Buses</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- medium-t.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- long-term</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- medium-t.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- long-term</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Passenger Cars</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- medium-t.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- long-term</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- medium-t.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- long-term</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Vans</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Natural Gas</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- medium-t.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- long-term</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>Hydrogen</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- short-term</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>-</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- medium-t.</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>- long-term</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>+</td>
<td>0</td>
<td>0</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
</tbody>
</table>

- means: worse than the diesel combustion engine
-- means: much worse than the diesel combustion engine
O means: in the same manner than the diesel combustion engine
+ means: better than the diesel combustion engine
++ means: much better than the diesel combustion engine

Tab. 7.6: Reference Behavior Pattern of the Hydrogen Propulsion System in different Market Sectors
As the table above shows, hydrogen powered city buses and vans can be introduced into the market in a medium-term (5-10 years away) because almost all kinds of customer requirements can be fulfilled in the same or better way than by the conventional propulsion system. In contrast to this, hydrogen powered passenger cars are only long-term options (more than 10 years away) mainly due to the higher life-cycle costs and the lack of a sufficient refueling infrastructure.
8. Action Plan for Implementation

In the following section, system analysis and computer modeling (STELLA) are used in order to predict when a hydrogen powered transport system is likely to be introduced. In addition, several strategies for implementing the hydrogen propulsion system into the market are evaluated. By doing this, two scenarios per case-study are developed to assess the effects and consequences of different strategies and to estimate both the market potentials and the date of a market penetration. The results indicate what measures would be important in a market strategy aimed at implementing the hydrogen propulsion system.

STELLA MODEL

A Stella model (figure A.VI.1, A.VI.2 and A.VI.3) for each case-study is built with the CLD in figure 4.2 as a basis. Some factors have been subdivided to give a more accurate input. This is especially the case with life-cycle costs of both hydrogen and diesel. The life-cycle costs are divided into that of engine cost per km, and that of fuel cost per km since these two groups have very different reference behavior patterns regarding the potential for cost reduction in the future. In addition, the Stella model includes four different strategies for producing hydrogen, namely chemical surplus production (hydrogen as a by-product) and electrolysis based on both conventional electricity (non-renewable energy source) and wind and hydro power (renewable energy sources). The chemical surplus production of hydrogen as a by-product is limited by the production capacity. The legal and societal requirements are not explicitly shown in the Stella model, but these requirements are included through the items "Green Tax", "Taxes on Hydrogen" and "Motor Vehicle Tax". Furthermore, it is assumed that the supply of hydrogen is equal to the demand for it.

ASSUMPTIONS AND LIMITATIONS IN GENERAL

The following assumptions, which are mainly based on the previous chapters, are universally valid for the three case-studies ("City-Buses", "Vans" and "Passenger Cars"):

**Engine Cost per km**
- The engine cost of a fuel cell technology is assumed to amount currently to around $3-4.000 per kW, around $1.000 by the year 2006 and around $40 per kW at a 500.000 units per year production level in a long term-view (by the year 2020).
- The engine cost of a diesel powered internal combustion engine is assumed to amount to around 30 per kWh. In addition, the engine costs are assumed to be fixed.

**Fuel Cost per km**
- The fuel cost of hydrogen (by product) is assumed to amount to around 80 Pf/m³, which is equivalent to 27 Pf/kWh. In addition, it is assumed that the current production of hydrogen as a by-product would be sufficient to fuel a fleet of about 12.000 fuel cell buses.
- The total fuel cost of hydrogen based on electrolysis are shown in the following:

<table>
<thead>
<tr>
<th>Electrolysis based on</th>
<th>Wind Power</th>
<th>Hydro Power</th>
<th>Conventional Electricity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Currently</td>
<td>45 (Pf/kWh)</td>
<td>35 (Pf/kWh)</td>
<td>32 (Pf/kWh)</td>
</tr>
<tr>
<td>by the year 2010</td>
<td>28 (Pf/kWh)</td>
<td>25 (Pf/kWh)</td>
<td>25 (Pf/kWh)</td>
</tr>
</tbody>
</table>

It is assumed that the total fuel cost of hydrogen can be significantly reduced in the short and medium-term due to further improvements and new breakthroughs in the technologies.
Taxes, Capital Interest and Inflation (Annual Price Increase in Average)
- The value added tax, tariffs of duties and the annual price increase on average are not considered in the following scenarios.
- The capital interest is assumed to amount to around 8% per year.

3.1 Action Plan "City Buses"

8.1.1 Technological Strategy for Implementation

The implementation strategy of hydrogen propulsion systems in the market sector "City Buses" is shown in the following figure 8.1. This figure illustrates the possible and suggested (highlighted squares) technological paths from the production of hydrogen based on primary energy sources to the utilization of the energy carrier as a fuel for vehicles.

Figure 8.1: Possible and Suggested Entire Chain of the Hydrogen Propulsion System - City Buses

Figure 8.1 is the results of the previous chapters. Accordingly, the hydrogen propulsion system can be introduced through the following three implementation strategies, which are illustrated by the yellow colored squares in the above shown figure:

- **Conventional electricity** based on fossil fuels can be used as a temporary solution for powering an electrolyzer. This could be an ideal starter for the introduction of hydrogen into the market in a short-term view due to both the high level of availability (grid of electricity) and the lower costs compared to renewable energy sources. Furthermore, the on-site production of hydrogen based on conventional electricity can be used as a frequency control measure. By doing this the surplus capacity of electricity, which is necessary to control the fluctuation of demand for electricity and to ensure a total level of satisfaction of needs at any time, can be utilized for producing hydrogen.

- The use of gaseous hydrogen produced as a by-product from refineries, electrolytic production (mostly from hydro power) or from other chemical surplus production (mostly chlorine-alkaline-electrolysis) could be a further short-term oriented implementation strategy. Currently, the by-product is partly burnt off because there is almost no demand for it.

After implementing the hydrogen propulsion system into the market sector "City Buses" through the measures described above, the entire energy system can be improved by using...
wind and hydro power as renewable energy sources in a medium-term. In this case, a whole energy chain based on renewable energy can be achieved. Aside the "by-product-strategy", the above described strategies includes the following items: an on-site production and compression of hydrogen at the bus depot and the use of both the PEM fuel cell technology and gas cylinders of compressed hydrogen.

8.1.2 Scenarios

ADDITIONAL ASSUMPTIONS “CITY BUSES”

Rolling Stock; Demand; Lifetime and Driving Range
- The initial stock of city buses is about 82,000 (annual growing rate: 0.2 %).
- The demand for new buses is dependent on the lifetime of city-buses and the annual growing rate of the additional need for city buses (extension of the bus fleet).
- The driving range of city buses is assumed to be 250 km per day. The buses will be used 300 days per year. The total lifetime of city buses amounts around 12 years.

Fuel Consumption per km and Fuel Cost per km
- The fuel consumption rate of city buses is assumed to amount to 2.4 kWh per km for fuel cell buses and 4.5 kWh per km for city buses powered by an internal combustion engine (Consulctra Management Consulting GmbH, 1999).
- The fuel costs for diesel are assumed to amount to 110 Pf/liter. The annual price increase of diesel is assumed to be 1 % caused by the price policy of OPEC.

Customer Requirements
- The customer requirements regarding technology, service infrastructure, availability and acceptance can be fulfilled by the year 2004.

Motor Vehicle Tax
- It is assumed that the motor vehicle tax will amount to around DM 1,300 per year for diesel powered buses and to around DM 650 for hydrogen powered buses (Bundesministerium der Finanzen, 1999).

Scenario 1: "Business as usual"
The scenario "Business as usual" is based on the assumption that the German government will continue their passive policy in the transport sector. The passive, reactive policy is described in section 6. Accordingly, a significant increase in the "Green Tax" on fossil fuels and further supporting activities like economic incentives for the hydrogen propulsion system cannot be expected in the short and medium-term. Therefore it is assumed that the government will only support the hydrogen propulsion system through the following measures:

- a temporary exclusion of additional taxes on hydrogen (like the "Green Tax" and "Tax on Mineral Oil") and
- a reduction of the "Motor Vehicle Tax" on hydrogen by 50 %.

This means that the industry (car-manufacturers and producers/distributors of hydrogen) and the public transportation companies mainly have to bear the additional costs and the risk of investment. Thereby, the economic viability and competitiveness of hydrogen are the main determinants for a market penetration of the hydrogen propulsion system in the future. In the following sections, it is assumed that the industry can achieve its defined short and medium-
term goals described in section 3. Furthermore, it is assumed that the public transportation companies will accept higher the cost of the hydrogen propulsion system (up to 10% of additional costs) in order to fulfill the societal-driven and legal requirements. The results of the scenario are shown in the following two figures.

Figure 8.2: Switch to Hydrogen: Scenario "Business as usual" - City Buses (see also Figure A.V.9; Cost per km: Pfennige per km; CGH2 and Diesel Buses: Total Number of Buses)

Due to the higher life-cycle costs per km of hydrogen (mainly caused by the higher engine cost per km, see figure A.V.3), a market penetration of the fuel cell technology is unlikely before the year 2014. Despite a temporary exclusion and reduction of taxes on hydrogen, the life-cycle costs are still too high. As the figure above shows, only demonstrations and pilot projects will be carried out within the next 15 years in order to test and demonstrate hydrogen powered buses. Accordingly, only 123 hydrogen powered buses will be in use by the year 2014. Due to a significant decrease of the life-cycle cost of the fuel cell technology, a market penetration of the hydrogen propulsion system can be expected during the time period 2014 to 2031. Accordingly, the total number of hydrogen powered buses will increase up to 28,729 by the year 2021. This is around one third of the total rolling stock of city buses in Germany. After this, the total number of hydrogen powered buses will further increase up to 42,409 buses (slightly more than 50% of the total rolling stock) by the year 2023 and up to 82,200 buses (100% of the total rolling stock) by the year 2031. As figure 8.3 illustrates, the market penetration of hydrogen will be achieved through the following three different implementation strategies. First of all, gaseous hydrogen produced as a by-product from refineries, electrolytic production (mostly from hydro power) or from other chemical surplus production (mostly chlorine-alkaline-electrolysis) will be used to introduce the hydrogen propulsion system into the market. Due to the relatively low life-cycle cost of the introduction strategy (strategy 1: red colored line), the demand for hydrogen powered buses will increase up to 12,000 buses by the year 2015. At that time, the limit of the production capacity of the "by-product" will be achieved resulting in a temporary decrease of the demand for the hydrogen propulsion system due to the higher life-cycle costs of hydrogen. At this time, hydrogen will be produced through electrolysis which will be based on conventional electricity (strategy 2: blue colored line). Nevertheless, the second strategy will support the introduction of the on-site production of hydrogen (electrolysis) into the market. In addition it will pave the way for renewable energy sources (wind and hydro power) into the transport sector, which will occur by the year 2033 (strategy 3: orange colored line).
As figure 8.3 illustrates, the choice of the energy source for producing hydrogen is mainly dependent on the economic competitiveness of the different sources compared to diesel. This means that renewable energy sources (wind and hydro power) will only be chosen if their fuel costs are lower than the fuel cost of non-renewable energy sources or if their fuel costs do not exceed the fuel cost of diesel by more than 10%, which is the limit that the public transportation companies will find acceptable.

The described scenario “Business as usual” is neither a worst-case scenario or an unrealistic and pessimistic viewpoint. At the end of the research work, a new agreement was carried out by the German government, which will be put into force at the end of the year 1999. The agreement (initialized by the “Green Party” (Bündnis 90/Die Grünen)) contains a decrease of the “Green Tax” on mineral oil by 3 Pf per liter for the public transport companies in order to increase the competitiveness compared to the private transport sector. The results of the new regulation are shown in figure A.V.1 and 2. Accordingly, the total replacement of diesel powered buses and the establishment of an entire energy chain based on renewable sources will be delayed by 8 years compared to the scenario “Business as usual”.

**Scenario 2: "Strong-man Act"**

Scenario 2 is based on the assumption that the main market players will have a big interest in implementing the hydrogen propulsion system into the field of the market sector "City Buses" as soon as possible. Therefore, they will consolidate their power through cooperative work in order to accelerate the market penetration of the hydrogen propulsion system. In addition, the cooperative activities will be supported by the German government through the following measures and economic incentives:

- a temporary exclusion of any tax on hydrogen;
- a further increase of the green tax on mineral oil (just for “City Buses”) by 12 Pf/liter during the time period 2004-2009; if necessary, the green tax can be partly used to cover the subsidies for demonstrations and pilot projects.
The driving forces of the pro-active policy of the German government could be the following: to achieve a reduction of the environmental impacts of road traffic, an increase in the competitive power of the German industry and a reduction of the rate of unemployment.

The results of the scenario are shown in the following figures.

Figure 8.4: Switch to Hydrogen: Scenario "Strong-man Act" - "City Buses"

Due to both the cooperative activities of the main market players and the supporting measures of the government, market penetration of the hydrogen propulsion system can be expected by the year 2012. Accordingly, the total number of hydrogen powered buses will increase up to 27,484 by the year 2016, which is around one third of the total rolling stock of city buses in Germany. After this, it will further increase up to 41,160 (slightly more than 50% of the total rolling stock) by the year 2018 and up to 82,200 buses (100% of the total rolling stock) by the year 2024 (7 years earlier compared to the scenario "Business as usual").

Figure 8.5: The Figure illustrates both the total production cost (Pf per km) of diesel and hydrogen (based on different energy sources) and the action plan for the implementation and market penetration of the hydrogen propulsion system in the field of "City Buses" (black colored line) - Scenario "Strong-man Act"
As figure 8.5 shows, the establishment of an entire energy chain based on renewable sources (strategy 2: orange colored line) can be achieved 24 years earlier (by the year 2009) compared to the scenario "Business as usual" (by the year 2033). These strategies will be supported by using hydrogen produced as a by-product (strategy 1: red colored line).

8.2 Action Plan "Vans"
The implementation strategies for "Vans" that are described below focus on fleet vehicles characterized by both a restricted range (around 200 - 300 km per day) and a local operational area. The fleet vehicles are operated by the company "Hermes Versand Service". Due to the fact that the driving conditions of both bus and vehicle fleets are similar, the following scenarios are also based on the technological strategies for implementation that are described above (figure 8.1). The following additional assumptions are made in the model:

**ADDITIONAL ASSUMPTIONS "VANS"

**Rolling Stock; Demand; Lifetime and Driving Range**
- The initial stock of vans is about 1,800.
- The demand for new vans is dependent on the lifetime of city-buses and the annual growth rate for the additional need for city buses (extension of the fleet).
- The driving range of vans is assumed to be 200 km per day. The vans will be used 280 days per year. The total lifetime of vans amounts around 6 years.

**Fuel Consumption and Cost per km**
- The fuel consumption rate of vans is assumed to amount to 0,7 kWh per km for fuel cell vans and 1,2 kWh per km for vans powered by an internal combustion engine.
- The fuel costs of diesel are assumed to amount to 115 Pf/liter. The annual price increase of diesel is assumed to be 1 % caused by the price policy of OPEC.

**Customer Requirements**
- The customer requirements regarding technology, service infrastructure, availability and acceptance can be fulfilled by the year 2004.
- It is assumed that the company "Hermes Versand Service" will accept higher life-cycle costs compared to diesel (up to 2,5 %) in order to fulfill their self-obligation of saving 25 % CO₂ by the year 2005. One of the driving forces behind the self-obligation is the goal of achieving a competitive advantage through a higher environmental-friendly image.

**Motor Vehicle Tax**
It is assumed that the motor vehicle tax will amount to around DM 257,40 per year for diesel powered buses and to around DM 128,70 for hydrogen powered buses (Bundesministerium der Finanzen, 1999).

**Scenario 1: "Business as usual"**
The conditions of the following scenario are similar to those of the scenario "Business as usual" for "City Buses". The results of the scenario are shown in the below figures.
A market penetration of hydrogen powered vans is unlikely before the year 2015 mainly due to the higher life-cycle cost of hydrogen (mainly engine cost; see figure A. V. 4) compared to diesel. Despite a temporary exclusion and reduction of taxes on hydrogen, the life-cycle costs are still too high. Therefore, only demonstrations and pilot projects will be carried out within the next 16 years. Market penetration of the hydrogen propulsion system can be expected during the time period 2015 to 2017 caused by a significant decrease in the life-cycle cost of the hydrogen propulsion system. The transition time will amount to three years due to the short duration of usage. As figure 8.7 illustrates, the establishment of an entire energy chain based on renewable sources can be achieved by the year 2009 at the earliest (on-site production of hydrogen through electrolysis of electricity based on wind and hydro power). This strategy (strategy 2: orange colored line) could be supported alternatively by using hydrogen produced as a by-product (strategy 1: red colored line) or through electrolysis based on conventional electricity from a grid (blue colored line).

Figure 8.6: Switch to Hydrogen: Scenario "Business as usual" - "Vans" (Cost per km: Pfennige per km; CGH2 and Diesel Vans: Total Number of Vans)

Figure 8.7: The Figure illustrates both the total production cost (Pf per km) of diesel and hydrogen (based on different energy sources) and the action plan for the implementation and market penetration of the hydrogen propulsion system in the field of "Vans" (black colored line) - Scenario "Business as usual"
Scenario 2: "Strong-man Act"

Scenario 2 is also based on the assumption that the main market players will have a big interest in implementing the hydrogen propulsion system into the field of the market sector "Vans" as soon as possible. Therefore, they will carry out several cooperation activities in order to accelerate the market penetration of the hydrogen propulsion system. In addition, the cooperative activities will be supported by the German government through the following measures and economic incentives:

- a temporary exclusion of any tax on hydrogen;
- an increase of the green tax on mineral oil (just for "Vans") by 12 Pf/liter during the time period 2004-2007; if necessary, the green tax can be partly used to cover the subsidies for demonstrations and pilot projects;

The results of the scenario are shown in the following figures.

![Graph 3](Graph 3.png)

Figure 8.8: Switch to Hydrogen: Scenario "Strong-man Act" - "Vans"

Despite both the cooperative activities of the main market players and the financial support measures of the government, a market penetration of the hydrogen propulsion system cannot be achieved before the year 2009 due to the higher life-cycle cost of the hydrogen propulsion system. For instance, the additional annual cost of the hydrogen propulsion system will amount to DM 9,517 per van by the year 2008. This means that the hydrogen propulsion system will exceed the annual cost of diesel by 35 %, which is not acceptable for the company "Hermes Versand Service". Furthermore, the additional cost cannot be equalized by further financial support measure like subsidies and taxes. By the year 2009, the life-cycle cost of the hydrogen propulsion system will become competitive with diesel. Therefore, the total number of hydrogen powered vans will increase up to 1.800 (100 % of the total rolling stock) by the year 2012 (5 years earlier compared to the scenario "Business as usual").
Figure 8.9: The Figure illustrates both the total production cost (Pf per km) of diesel and hydrogen (based on different energy sources) and the action plan for the implementation and market penetration of the hydrogen propulsion system in the field of "Vans" (black colored line) - Scenario "Strong-man Act"

As figure 8.9 shows, the establishment of an entire energy chain based on renewable sources (strategy 2: orange colored line) can be achieved 3 years earlier (by the year 2006) than the scenario "Business as usual" (by the year 2009). This strategy will be supported alternatively by using hydrogen produced as a by-product (strategy 1: red colored line) or through electrolysis based on conventional electricity from a electricity grid (blue colored line).

8.3 Action Plan "Passenger Cars"

8.3.1 Technological Strategy for Implementation

The implementation strategy of hydrogen propulsion systems in the market sector "Passenger Cars" is shown in the following figure, which illustrates the possible and suggested (highlighted squares) technological paths from the production of hydrogen based on primary energy sources to the utilization of the energy carrier as a fuel for vehicles.

![Figure 8.10: Possible and Suggested Entire Chain of the Hydrogen Propulsion System -Passenger Cars](image-url)
Accordingly, the hydrogen propulsion system can be introduced through the following two implementation strategies, which are illustrated by the yellow colored squares in the above shown figure:

- The onboard methanol fuel processing technology (compared to hydrogen propulsion systems based on gaseous or liquid hydrogen) could be an ideal starter for hydrogen because of the following two advantages: methanol can be more easily stored onboard the vehicle and it does not require a completely new distribution system and refueling infrastructure.
- Similar performances can be achieved by using a low-temperature catalytic partial oxidation (POX) system as an onboard hydrogen processing technology extracted from gasoline.

After implementing the fuel cell technology into the market sector ”Passenger Cars” through the aforementioned measures, the entire energy system can be improved by using wind and hydro power as renewable energy sources in the medium-term. In this case, a whole energy chain based on renewable energy can be achieved.

In the following sections, the strategies for market implementation and penetration of gaseous and liquid hydrogen are described.

8.3.2 Scenarios
The following scenarios are based on both the technological strategies described above for implementation (figure 8.10) and a Stella model, which is shown in figure A.VI.3. The following additional assumptions are made in the model:

Rolling Stock; Demand; Lifetime and Driving Range
- The initial stock of passenger cars in Germany is about 41.670.000 vehicles as of the year 1999.
- The demand for new passenger cars is dependent on their lifetime and the annual growth rate in the additional need for vehicles. In this case, it is assumed that the rolling stock will increase up to 49,9 million vehicles by the year 2010 and up to 51,5 million vehicles by the year 2020.
- The driving range of passenger cars is assumed to be around 650 km per fill-up. The passenger cars will be used for 250.000 km in total. The total lifetime of passenger cars amounts around 12 years on average.

Conventional Fuel
- Due to the similar life-cycle cost and driving performances, diesel and gasoline are summarized as one “competitor” for hydrogen in the following figure. By doing this, the term “conventional fuels” is used which is based on real data of gasoline as a reference.

Fuel Consumption Fuel Cost per km
- The fuel consumption rate of passenger cars is assumed to amount to 0,35 kWh per km for fuel cell vehicles and to 0,7 kWh per km for vehicles powered by an internal combustion engine.
- The fuel costs of gasoline are assumed to amount to 175 P/liter. The annual price increase of gasoline is assumed to amount to around 1 % caused by the price policy of OPEC.
Life-cycle Cost
- It is assumed that that the passenger car customer cannot or will not calculate the total life-cycle cost of the different propulsion systems including the capital interest, the compound interest and the total fuel consumption. Therefore, the following scenarios are based on the assumption that the customer will overestimate the total capital cost per km and underestimate the total fuel cost per km.

Customer Requirements
- Aside from expenses, service infrastructure and driving range, the customer requirements can be fulfilled by the year 2004.
- It is assumed that most of the customers won’t accept higher life-cycle cost compared to gasoline.

Motor Vehicle Tax
It is assumed that the motor vehicle tax will amount to 100 Pf/100 cm³ per year for gasoline and hydrogen powered vehicles. The motor vehicle tax will increase up to 132 Pf/100 cm³ per year by the year 2004 (Bundesministerium der Finanzen, 1999). Furthermore, a temporary exclusion of the “motor vehicles tax” for 5 years can be expected for vehicles characterized by a low emission and fuel consumption level.

Scenario 1: "Business as usual"
The conditions of the following scenario are similar to them of the scenario "Business as usual" for "City Buses". In addition, it is assumed that the mineral oil companies will start to build the service infrastructure for hydrogen when all other kind of customer requirements are already fulfilled. In this case, first of all the mineral oil companies will establish around 3,500 service stations mainly in highly populated areas in order to accelerate the market penetration. After doing this, the further development of the service infrastructure will be dependent on the demand for CGH₂ powered passenger cars and vice versa resulting in the following reinforcing loop: the introduction of the first refueling stations will lead to an increase of the demand for CGH₂ powered passenger cars resulting in a further development of the service infrastructure leading to an increase of the demand for... and so on. Furthermore, the mineral oil companies will support a development of an European refueling infrastructure for hydrogen at a later date. The results of the scenario are shown in the below figures.

Figure 8.11: Switch to Hydrogen: Scenario "Business as usual" - "Passenger Car" powered by CGH₂ (Cost per km: Pfennige per km; CGH₂ and Conventional Fuel Vehicles: Total Number of Vehicles)
As figure 8.11 illustrates, a market introduction of CGH₂ powered passenger cars cannot be expected within the next 16 years to come due to the following obstacles (figure 8.12): Despite of a temporary exclusion and reduction of taxes on hydrogen, the life-cycle cost (blue colored line) are still too high until the year 2013. At that time, the life-cycle cost of the hydrogen propulsion system will become competitive compared to diesel. But still, the market introduction of CGH₂ powered passenger cars is unlikely due to a miscalculation of the life-cycle cost (red colored line) by customers, a limited driving range (green colored line) and the absence of a wide-spread service infrastructure (violet colored line). Only the fulfillment of all customer requirements will lead to an increase of the demand for CGH₂ powered passenger cars resulting in a market penetration. In this case, the total number of CGH₂ powered vehicles will increase from 6.300 vehicles (2015) up to 15.650.000 by the year 2024, which is around one third of the total rolling stock of passenger cars in Germany. After that, it will further increase up to 25.550.000 vehicles (slightly more than 50 % of the total rolling stock) by the year 2026 and up to 52.280.000 (100 % of the total rolling stock) by the year 2035. On the contrary, LH₂ powered passenger cars can be introduced a couple of years earlier (see figures A.V.5 and 6) due to better performance in driving range.

**Scenario 2: "Strong-man Act"**

This scenario is also based on the assumption that the main market players will have a big interest in implementing the hydrogen propulsion system into the field of the market sector "Passenger Cars" as soon as possible. Therefore, they will carry out several cooperative activities in order to accelerate the market penetration of the hydrogen propulsion system mainly by building up 4.500 service stations by the year 2012 and 3.500 by the year 2013. The cooperative activities will be supported by the German government through the following measures and economical incentives:

- a temporary exclusion of any tax on hydrogen;
- a continuation of the green tax on mineral oil (just for "Passenger Cars") by a slightly higher rate (8 Pf/liter) during the time period 2004-2011.

If necessary, the green tax can be used to cover the subsidies for both demonstration projects and for building up the service infrastructure in Germany. The results of the scenario are shown in the following figures.
Despite of the development of a service infrastructure, a replacement of passenger cars powered by conventional fuels (gasoline or diesel) cannot be achieved before the year 2030. As figure 8.14 illustrates, mainly the limited driving range (green colored line) and the higher life-cycle cost (blue colored line) will prevent a market penetration of CGH\textsubscript{2} powered passenger cars at an earlier date. Therefore, it can be expected that the German government will support alternatives characterized by better performance in driving range and life-cycle cost in order to be able to reduce the environmental impact of the road traffic in a short and medium-term. The use of liquid hydrogen as an energy carrier could be one option (see figures A.V.7 and 8). Graphite nanofibres could be another alternative in the future. Researchers at Northeastern University, USA, claim that they succeeded in developing graphite nanofibres that can store up to 3 times of their own weight in hydrogen under pressure at room temperature. This technology, which is still in the prototype phase, could provide a technological break-through in the onboard storage technology due to the high volumetric and gravimetric energy densities (Jung, 1999).
9. Discussion

As mentioned before, a displacement of conventional fuels based on renewable energy sources is one step towards a more sustainable transport system in Germany. Nevertheless, there are several additional necessary criterion that also have to be fulfilled in order to achieve sustainability in a transport system. First of all, the total consumption level per person must be reduced by both supporting the public transport sector and reorganizing the conventional city-planning activities. Also important is increased efficiency - getting more from less - and an increase in recycling and reuse of used products. All these criterion point in the same direction: achieving sustainability is impossible if its many aspects are not addressed simultaneously. Anyway, this study shows that hydrogen, as a new energy carrier in the private and public transport sector, will provide huge potentials towards reducing the impacts on the social and ecological environment. Accordingly, the use of hydrogen would lead to a reduction of harmful emissions to zero (during the usage) and to a higher material and energy efficiency per service unit over the entire life-cycle compared to fuels currently in use. In addition, it would make it possible to use renewable energy sources in the transport sector resulting in a decreased exploitation of fossil fuels in the future.

Despite of the ecological benefits of hydrogen, there are several considerable barriers to entry. In practice, these are not just technological difficulties to overcome. In the case of "City Buses" and "Vans", the technological requirements can be fulfilled in a short-term view. The technology already exists to produce hydrogen, to transport, to store and to use it safely (Hart, 1997). But the total life-cycle costs are still too high and there seems to be no need for it (see section "Legal Requirements"). In addition, there are also different blocking coalitions who are able to continue delaying the introduction of stricter emissions standards and legal requirements which would support the market introduction of hydrogen. Under these circumstances, a market introduction of hydrogen is unlikely in a short and medium-term unless changes can be made in the cost structure and policy making process. If sustainability becomes a real political driver the chances for an accelerated market introduction of hydrogen into the transport sector become greater. This is one of the main results of the scenarios carried out for the different case-studies. The "Business as usual" scenarios illustrate that a passive reactive environmental policy will lead to a delay of a market introduction of hydrogen resulting in a continuation of the current non-sustainable transport system. After the implementation, it would indirectly support the production of hydrogen based on non-renewable energy sources due to the lower cost.

On the contrary, the "Strong-man-act" scenarios show potentials of cooperative activities between the main market players including a pro-active environmental policy. In this case, legal measures would lead to an acceleration of the implementation of an entire energy chain based on renewable energy sources in the transport sector. Therefore, a pro-active environmental policy, including stricter regulations, the "polluter pay principle" and an externalization of external costs through several financial measures like the establishment of a "CO\textsubscript{2}-Tax", are recommended. Furthermore, the hydrogen propulsion system must be subsidized in the beginning. The subsidization can be covered for instance by a continuation of the green tax on mineral oil. But first of all, a cooperation between the main market players, namely car manufacturers, oil companies, utilities and the German government, is needed in order to concentrate and consolidate their power for a market introduction of hydrogen as a common uniform energy strategy for the transport sector in Germany. In this case, the hydrogen propulsion system could be introduced into the market through several technology push and demand pull strategies at the same time from different sites.
But the change of the policy-making-process should not only be limited on putting the focus on sustainability. A change of the whole process including the way of thinking is needed. This means that problems have to be analyzed in an interdisciplinary and comprehensive way including time delays and interactions between the different items. Otherwise, policy agreements and measures can evolved into something very different from what was first envisioned like the decrease of the “Green Tax” on mineral oil for the public transport sector in order to decrease the impacts on the environment by increasing the competitiveness of the public transport sector compared to the private transport sector (see section 8).

In addition, it is necessary to increase both the level of acceptance of the users and the knowledge of the society about the hydrogen propulsion system. Therefore increasing demonstration projects within the next years to come combing them with different public relations and education programs is suggested. As described in section 8, the market introduction of the hydrogen propulsion system should start with the implementation of hydrogen powered buses. After a successful set up in business, hydrogen powered vans can also be introduced into the market, followed by the introduction of other fleet vehicles. Finally, hydrogen powered passenger cars can enter the market provided that the problems regarding higher lifecycle costs, driving range and infrastructure can be solved. The expected time-scales are uncertain and mainly dependent on both the different actors’ level of willingness to change and the efficiency of the negotiation and cooperative processes. The efforts of implementing a hydrogen propulsion system should be focused on the fuel cell technology powered by gaseous hydrogen because of the better performances in energy efficiency and emissions which are mainly determining the level of impact on the ecological environment.

In the case of fleet vehicles, the suggested implementation plans can be carried out through a national “go-it-alone” approach of the German industry and government. In addition, the implementation plans are applicable for the worldwide market sector. On the contrary, the implementation plan for “Passenger Car” requires an international perspective. Especially, the need for a common uniform service and refueling infrastructure has to be fulfilled through international agreements and cooperation.

Ultimately, the study shows that at some point in the future hydrogen will become the major fuel in the transport sector mainly due to better performance of the fuel cell technology regarding energy efficiency, emission standard and the capability to use renewable energy sources. These factors that are very important with respect to an expected increase of the total demand for vehicles worldwide and their negatively impacts on the local and global environment, drive the continually increasing interest in fuel cells by vehicle manufacturers, energy companies, commercial and industrial users, environmentalists, politicians, the media and the public. In fact, seven of the world’s largest auto manufacturers have publicly stated their intention to offer fuel cell powered cars around 2004. The ongoing investment activities and demonstration projects shows the willingness of the main market players to change the current, non-sustainable transport sector towards a hydrogen powered system. The potential for a change is certainly there, but it is still unknown and speculative when hydrogen powered transport system is likely to be introduced. The above shown “Business as usual” and “Strong-Man-Act” scenarios show different predictions and time scales for a market introduction of hydrogen powered vehicles. Worse-case scenarios are not explicitly shown. In this case, a market introduction will be delayed or prevented caused by different circumstances like “no interest of the government”, “development of new alternative technologies” or “cost reduction targets can not be achieved by the industry”. As a result of
this, hydrogen powered vehicles will only be used in small specific niche markets like climatic health-resorts or exhibition centers.

10. Conclusion

It has been argued above that a shift in the current transport system towards a more sustainable system based on hydrogen is mainly dependent on the main market players' willingness to change, especially of the German government. To accomplish the transition, a cooperation between the main market players in necessary and an agreement about hydrogen as the common uniform energy strategy for the transport sector in Germany are required. Furthermore, the economic system of pricing, subsidizing and charging the transport system needs to be changed. It is essential that several demand pull and technology push strategies are addressed simultaneously from different sites.
References


Andersson et al. (1996): Material constraints in a global energy scenario based on thin-film solar cells, Institute of Physical Resource Theory, Chalmers University of Technology and Göteborg University, Göteborg


Behrmann, K. (1999 a): Brennstoffzellen im ÖPNV-Einsatz; Publication of Hamburger Hochbahn AG


BMW (1999 a): Wasserstoffantrieb, Brochure of BMW, Augsburg


BMW (1999 c): BMW-7-Series: www.bmw.de/auto/index.htm


Bundesregierung der Bundesrepublik Deutschland (1999): Pressenachrichten, http://www.bundesregierung.de/05/Themenv.htm


Daimler-Benz (1996): NECAR II – Driving without Emissions; Brochure of Daimler-Benz, Stuttgart


DaimlerChrysler (1999 a): NECAR 4 – The alternative; brochure of DaimlerChrysler, Stuttgart

DaimlerChrysler (1999 b): NECAR: http://www.daimlerchrysler.de/cgi-bin/searchframe.pl


Ebner (1999): Interview with Mister Ebner (DaimlerChrysler) carried out by Mister Weinmann (HEW), Hamburg


Hydrogen & Fuel Cell Letter (May 1996), Editor and Publisher: Peter Hoffmann, Rhinecliff USA

Hydrogen & Fuel Cell Letter (June 1997), Editor and Publisher: Peter Hoffmann, Rhinecliff USA

Hydrogen & Fuel Cell Letter (January 1999), Editor and Publisher: Peter Hoffmann, Rhinecliff USA

Hydrogen & Fuel Cell Letter (April 1999), Editor and Publisher: Peter Hoffmann, Rhinecliff USA

Hydrogen & Fuel Cell Letter (June 1999), Editor and Publisher: Peter Hoffmann, Rhinecliff USA

Hydrogen & Fuel Cell Letter (July 1999), Editor and Publisher: Peter Hoffmann, Rhinecliff USA

Hydrogen & Fuel Cell Letter (November 1999), Editor and Publisher: Peter Hoffmann, Rhinecliff USA


Pfeiffer et al. (1991): Technologie-Portfolio zum Management strategischer Zukunftsgeschäftsfelder, Göttingen


Schaller (1999): Personal Interview with Mister Schaller: Senior Department Manager - Engineering Advanced Development - of MAN Utility Vehicle AG


Schuldit (1999): Personal Interview with Mister Schuldt (Hermes Versand Service), Hamburg

Steffes (1999): Personal Interview with Mister Steffes: Public Relations Manager of BMW, Hamburg


Umweltbundesamt (1997): Sustainable Germany - towards an environmentally sound development; a report of the working group "AGENDA 21/Sustainable Development" of the Federal Environmental Agency (Umweltbundesamt) of Germany, Berlin


Appendix I: Descriptions

CAUSAL LOOP DIAGRAM: Summarized Explanation of the Causal Loop Concept

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Meaning</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tail</td>
<td>Arrow → Head</td>
</tr>
<tr>
<td></td>
<td>The arrow is used to show causation. The item at the tail of the arrow causes a change in the item at the head of the arrow.</td>
</tr>
<tr>
<td></td>
<td>The + sign near the arrowhead indicates that the item at the tail of the arrow and the item at the head of the arrow change in the same direction. If the tail increases, the head increases; if the tail decreases, the head decreases.</td>
</tr>
<tr>
<td></td>
<td>The - sign near the arrowhead indicates that the item at the tail of the arrow changes in the opposite direction. If the tail increases, the head decreases; if the tail decreases, the head increases.</td>
</tr>
<tr>
<td></td>
<td>This symbol, found in the middle of a closed loop, indicates that a change in the item at the tail of the arrow will cause a change in the same direction for the item at the head of the arrow and vice versa. In this case, a change introduced to either element of the loop will continue to generate other changes in the same direction, as the loop is traced around and around. An R-symbol is placed in the center of the loop to suggest that it is a positive causal loop, one in which behavioral changes are reinforced. This system is called a reinforcing or escalating system.</td>
</tr>
<tr>
<td></td>
<td>This symbol, found in the middle of a closed loop, describes a negative feedback loop. Negative loops tend to keep systems under control by negating or counteracting change. The system is moving toward equilibrium. It is a balancing system.</td>
</tr>
</tbody>
</table>

Tab. A.I.1: Summarized Explanation of the Causal Loop Concept (Source: Adapted from Roberts et al., 1983)

EFFECTS OF EMISSIONS IN THE FIELD OF THE ROAD TRAFFIC

Figure A.I.2: Emissions of the Road Traffic and their Effects on Environment
The fuel cell consists of two electrodes, the anode and the cathode, which are separated from each other through an electrolyte. A platinum catalyst causes the hydrogen to separate into free electrons and protons (positive hydrogen ions) on the anode. The protons immigrate through the polymer membrane electrolyte, which is only a few tenths of a millimeter thick. Each ion leaves an electron behind so that negative charge accumulates on the hydrogen side and positive charge on the oxygen side. Due to the surplus of electrons at the anode and the deficit of electrons at the cathode, the generation of electric voltage is the consequence. The energy is produced by the bonding of hydrogen and oxygen to form pure water (Daimler-Benz, 1994; Ballard, 1999; Wurster 1997). In the NECAR vehicle, 300 of these cells are connected in series to two so-called stacks (Daimler-Benz, 1996).

<table>
<thead>
<tr>
<th>Extraction Treatment</th>
<th>Oil Well</th>
<th>Gas Well</th>
<th>Agroforestry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary Sources</td>
<td>Oil</td>
<td>Natural Gas</td>
<td>Water/Sunlight/Wind</td>
</tr>
<tr>
<td>Conversion Technologies</td>
<td>Refinery</td>
<td>Reduction of Pollutants</td>
<td>Trucks/Trucks/Ships/</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Ships/Ship</td>
</tr>
<tr>
<td>Distribution Technologies</td>
<td>Gasoline</td>
<td>Gas</td>
<td>Electricity</td>
</tr>
<tr>
<td>Energy Carrier</td>
<td>Compression</td>
<td>Electrolysis</td>
<td>Compression</td>
</tr>
<tr>
<td></td>
<td>Gasoline</td>
<td>Gas</td>
<td>Gaseous</td>
</tr>
<tr>
<td></td>
<td>Gas</td>
<td>Gaseous</td>
<td>Gaseous</td>
</tr>
<tr>
<td>On-Site Conversion Technologies</td>
<td>Compression</td>
<td>Electrolysis</td>
<td>Compression</td>
</tr>
<tr>
<td>Energy Carrier</td>
<td>Gas</td>
<td>Gaseous</td>
<td>Gaseous</td>
</tr>
<tr>
<td></td>
<td>Hydrogen</td>
<td>Hydrogen</td>
<td>Hydrogen</td>
</tr>
<tr>
<td>End-Use Technologies</td>
<td>/Combustion engine/</td>
<td>Fuel Cell Technology</td>
<td></td>
</tr>
<tr>
<td>Energy Services</td>
<td>1 km of travel</td>
<td></td>
<td></td>
</tr>
<tr>
<td>After-Treatment</td>
<td>Catalytic Converter;</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Appendix III: Demonstration and Pilot Projects

Figure A.III.1: NEBUS (Source: DaimlerChrysler, 1999 c)

Figure A.III.2: 4 Versions of NECAR (Source: Ballard, 1999 a)
Figure A.11.3: W.E.I.T. Project Hydrogen-Energy Iceland-Transfer (HEW, 1999)
## Appendix IV: Tables

<table>
<thead>
<tr>
<th></th>
<th>CO₂ g/kWh</th>
<th>CO g/kWh</th>
<th>NOₓ g/kWh</th>
<th>CO₂-equivalent g/kWh</th>
<th>SO₂ g/kWh</th>
<th>CH₄ g/kWh</th>
<th>NMVOC g/kWh</th>
<th>Dust g/kWh</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Gasoline</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 years</td>
<td>51,95</td>
<td>0,04</td>
<td>0,14</td>
<td>60,96</td>
<td>0,16</td>
<td>0,11</td>
<td>0,56</td>
<td>0,01</td>
</tr>
<tr>
<td>5-10 years</td>
<td>51,91</td>
<td>0,05</td>
<td>0,15</td>
<td>60,15</td>
<td>0,16</td>
<td>0,08</td>
<td>0,56</td>
<td>0,01</td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>50,77</td>
<td>0,04</td>
<td>0,14</td>
<td>58,94</td>
<td>0,16</td>
<td>0,08</td>
<td>0,56</td>
<td>0,01</td>
</tr>
<tr>
<td><strong>Diesel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 years</td>
<td>20,04</td>
<td>0,03</td>
<td>0,01</td>
<td>22,21</td>
<td>0,11</td>
<td>0,05</td>
<td>0,07</td>
<td>0,01</td>
</tr>
<tr>
<td>5-10 years</td>
<td>20,02</td>
<td>0,03</td>
<td>0,11</td>
<td>22,02</td>
<td>0,11</td>
<td>0,05</td>
<td>0,07</td>
<td>0,01</td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>19,64</td>
<td>0,03</td>
<td>0,01</td>
<td>21,61</td>
<td>0,11</td>
<td>0,05</td>
<td>0,07</td>
<td>0,01</td>
</tr>
<tr>
<td><strong>Natural Gas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 years</td>
<td>26,42</td>
<td>0,07</td>
<td>0,07</td>
<td>49,99</td>
<td>0,03</td>
<td>0,93</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td>5-10 years</td>
<td>26,32</td>
<td>0,07</td>
<td>0,07</td>
<td>49,92</td>
<td>0,03</td>
<td>0,93</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>23,75</td>
<td>0,07</td>
<td>0,06</td>
<td>46,94</td>
<td>0,03</td>
<td>0,92</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td><strong>Hydrogen (GH₂)¹</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 years</td>
<td>12,80</td>
<td>0,03</td>
<td>0,04</td>
<td>13,36</td>
<td>0,01</td>
<td>0,02</td>
<td>0,00</td>
<td>0,01</td>
</tr>
<tr>
<td>5-10 years</td>
<td>12,97</td>
<td>0,04</td>
<td>0,04</td>
<td>13,90</td>
<td>0,01</td>
<td>0,03</td>
<td>0,00</td>
<td>0,01</td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>11,42</td>
<td>0,03</td>
<td>0,03</td>
<td>12,24</td>
<td>0,01</td>
<td>0,03</td>
<td>0,00</td>
<td>0,01</td>
</tr>
<tr>
<td><strong>Hydrogen (GH₂)²</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 years</td>
<td>20,45</td>
<td>0,19</td>
<td>0,07</td>
<td>22,04</td>
<td>0,06</td>
<td>0,06</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td>5-10 years</td>
<td>20,46</td>
<td>0,19</td>
<td>0,07</td>
<td>22,02</td>
<td>0,06</td>
<td>0,06</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>20,13</td>
<td>0,19</td>
<td>0,06</td>
<td>21,66</td>
<td>0,06</td>
<td>0,06</td>
<td>0,01</td>
<td>0,01</td>
</tr>
<tr>
<td><strong>Hydrogen (GH₂)³</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>90,85</td>
<td>0,45</td>
<td>0,26</td>
<td>96,84</td>
<td>0,15</td>
<td>0,21</td>
<td>0,02</td>
<td>0,06</td>
</tr>
<tr>
<td><strong>Hydrogen (GH₂)⁴</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 years</td>
<td>13,30</td>
<td>0,02</td>
<td>0,21</td>
<td>25,86</td>
<td>0,02</td>
<td>0,02</td>
<td>0,02</td>
<td>0,01</td>
</tr>
<tr>
<td>5-10 years</td>
<td>11,66</td>
<td>0,02</td>
<td>0,18</td>
<td>22,43</td>
<td>0,02</td>
<td>0,01</td>
<td>0,01</td>
<td>0,00</td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>11,59</td>
<td>0,02</td>
<td>0,18</td>
<td>22,37</td>
<td>0,02</td>
<td>0,01</td>
<td>0,01</td>
<td>0,00</td>
</tr>
<tr>
<td><strong>Hydrogen (LH₂)⁵</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>&lt;5 years</td>
<td>20,90</td>
<td>0,04</td>
<td>0,06</td>
<td>29,03</td>
<td>0,04</td>
<td>0,32</td>
<td>0,00</td>
<td>0,02</td>
</tr>
<tr>
<td>5-10 years</td>
<td>14,07</td>
<td>0,03</td>
<td>0,04</td>
<td>22,16</td>
<td>0,03</td>
<td>0,32</td>
<td>0,00</td>
<td>0,01</td>
</tr>
<tr>
<td>&gt;10 years</td>
<td>12,04</td>
<td>0,03</td>
<td>0,04</td>
<td>20,11</td>
<td>0,01</td>
<td>0,32</td>
<td>0,00</td>
<td>0,01</td>
</tr>
</tbody>
</table>

1) Gaseous hydrogen based on hydro power generated in Germany
2) Gaseous hydrogen based on wind power generated in Germany
3) Gaseous hydrogen based on solar power (photovoltaic) generated in Germany
4) Gaseous hydrogen based on biomass generated in Germany
5) Liquid hydrogen based on hydro power generated in Norway


<table>
<thead>
<tr>
<th>Year</th>
<th>Gasoline/Diesel</th>
<th>Power/Electricity</th>
<th>Natural Gas</th>
<th>Mineral oil for heating</th>
<th>Coal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1999</td>
<td>+ 6 Pf/l</td>
<td>+ 2,0 Pf/l</td>
<td>+ 0,32 Pf/kWh</td>
<td>+ 4,0 Pf/l</td>
<td>0</td>
</tr>
<tr>
<td>2000</td>
<td>+ 6 Pf/l</td>
<td>+ 0,5 Pf/l</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2001</td>
<td>+ 6 Pf/l</td>
<td>+ 0,5 Pf/l</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2002</td>
<td>+ 6 Pf/l</td>
<td>+ 0,5 Pf/l</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2003</td>
<td>+ 6 Pf/l</td>
<td>+ 0,5 Pf/l</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>In Total</td>
<td>+ 30 Pf/l</td>
<td>+ 4,0 Pf/l</td>
<td>+ 0,32 Pf/kWh</td>
<td>+ 4,0 Pf/l</td>
<td>0</td>
</tr>
</tbody>
</table>

Tab. A.IV.2: “Green Tax” in Germany (Source: Umwelt- und Prognose Institut, 1999)
### Tab. A.IV.3: Legal Requirements - Passenger Cars (Source: Umweltbundesamt, 1999)

<table>
<thead>
<tr>
<th>Requirements for the road traffic (private cars) / Limiting values</th>
<th>NO$_X$ (g/km)</th>
<th>Particles (benzol and diesel soot compounds) (g/km)</th>
<th>CO (g/km)</th>
<th>HC (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EURO 1: 1992 (91/441/EWG)</td>
<td>0,62</td>
<td>0,18</td>
<td>0,51</td>
<td>0,11</td>
</tr>
<tr>
<td>Gasoline</td>
<td>1,02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td>0,28</td>
<td>2,7</td>
<td>0,23</td>
</tr>
<tr>
<td></td>
<td>0,63</td>
<td>0,08</td>
<td>1,1</td>
<td>0,07</td>
</tr>
<tr>
<td>EURO 3: 2000 (98/69/EG)</td>
<td>0,15</td>
<td>0,05</td>
<td>2,3</td>
<td>0,20</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0,50</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td>0,08</td>
<td>0,6</td>
<td>0,06</td>
</tr>
<tr>
<td>EURO 4: 2005 (98/69/EG)</td>
<td>0,08</td>
<td>0,025</td>
<td>1,0</td>
<td>0,10</td>
</tr>
<tr>
<td>Gasoline</td>
<td>0,25</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diesel</td>
<td></td>
<td>0,08</td>
<td>0,5</td>
<td>0,05</td>
</tr>
<tr>
<td>EURO 5: (ongoing negotiation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Needed limiting values with respect to Sustainability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>zero-emission</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Tab. A.IV.4: Legal Requirements - City Buses and Vans (Source: Umweltbundesamt, 1999)

<table>
<thead>
<tr>
<th>Requirements for the road traffic (City Buses and vans)</th>
<th>Weight/Mass (kg)</th>
<th>Particles (benzol and diesel soot compounds) (g/km)</th>
<th>CO (g/km)</th>
<th>HC+NO$_X$ (g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>EU-legislation 93/59/EG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group I (10/94)</td>
<td>&lt;= 1.250</td>
<td>0,18</td>
<td>3,16</td>
<td>1,13</td>
</tr>
<tr>
<td>Group II (10/94)</td>
<td>1.250 - 1.700</td>
<td>0,22</td>
<td>6,00</td>
<td>1,60</td>
</tr>
<tr>
<td>Group III (10/94)</td>
<td>1.700 - 3.500</td>
<td>0,29</td>
<td>8,00</td>
<td>2,00</td>
</tr>
<tr>
<td>Suggestion for the 2nd Version (ongoing negotiation)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Group I (Gasoline)</td>
<td>&lt;= 1.250</td>
<td></td>
<td>2,20</td>
<td>0,50</td>
</tr>
<tr>
<td>Group II (Gasoline)</td>
<td>1.250 - 1.700</td>
<td>0,08</td>
<td>4,00</td>
<td>0,06</td>
</tr>
<tr>
<td>Group III (Gasoline)</td>
<td>1.700 - 3.500</td>
<td>0,12</td>
<td>5,00</td>
<td>0,07</td>
</tr>
<tr>
<td>Group I (Diesel)</td>
<td>&lt;= 1.250</td>
<td>0,08</td>
<td>1,00</td>
<td>0,07</td>
</tr>
<tr>
<td>Group II (Diesel)</td>
<td>1.250 - 1.700</td>
<td>0,17</td>
<td>1,25</td>
<td>1,00</td>
</tr>
<tr>
<td>Group III (Diesel)</td>
<td>1.700 - 3.500</td>
<td>0,17</td>
<td>1,50</td>
<td>1,20</td>
</tr>
<tr>
<td>EU-legislation 91/542/EG</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EURO 1 (10/93)</td>
<td>&gt; 3.500</td>
<td>0,40</td>
<td>4,9</td>
<td>1,23 (HC) 9,0 (NO$_X$)</td>
</tr>
<tr>
<td>EURO 2 (10/96)</td>
<td>&gt; 3.500</td>
<td>0,14</td>
<td>4,0</td>
<td>1,1 (HC) 7,0 (NO$_X$)</td>
</tr>
<tr>
<td>EURO 3 (ongoing negotiation)</td>
<td>&gt; 3.500</td>
<td>0,08</td>
<td>2,10</td>
<td>0,66 (HC) 5,0 (NO$_X$)</td>
</tr>
<tr>
<td>OICA/ACEA</td>
<td>&gt; 3.500</td>
<td>0,16</td>
<td>5,45</td>
<td></td>
</tr>
<tr>
<td>FIGE</td>
<td>&gt; 3.500</td>
<td>0,10</td>
<td>2,10</td>
<td>- (HC) 5,0 (NO$_X$)</td>
</tr>
<tr>
<td>Needed limiting values with respect to sustainability</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>zero-emission</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1) OICA/ACEA = ESC (European Steady Cycle) + LRT (Load Response Test)
2) FIGE = ETC (European Transient Cycle)
<table>
<thead>
<tr>
<th>Case-Studies:</th>
<th>City-Buses (Hamburger Hochbahn AG)</th>
<th>Vans (Hermes Versand Service)</th>
<th>Passenger Cars</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>TECHNOLOGY</strong></td>
<td>- Acceleration: 40 km/h in 15 s</td>
<td>- Top speed: 100 km/h in 12,9 s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Driveability: 80 km/h</td>
<td>- Driveability: 80 km/h</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Driving Cycle: mainly short distances between stops; stop-and-go in towns</td>
<td>- Driving Cycle: mainly long distances between stops; high speed on highways</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Driving range: 300 - 350 km per day and around 500 per “fill-up”</td>
<td>- Driving range: 200 km per day</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Load carrying capacity: 106 persons (Standing-places: 68; Seats: 38)</td>
<td>- Load carrying capacity: 800 kg / 10,5 m³; Trend of the next decade: increase of the load carrying capacity and decrease of the total weight of empty vans</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Shape of vehicle: Low-flour-concept</td>
<td>- Shape of vehicle: Square Shape of Loading Space</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Life-span: 14 years</td>
<td>- Life-span: 3 years (Leasing Contract)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Comfort/Safety: High standard for Passenger; medium standard for User (driver of the bus)</td>
<td>- Comfort/Safety: Trailer Coupling; Leasing and Maintenance Contract; Newest State of Technology; Maintenance and Repairable/-friendly Design</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Features and options: Maintain- and Repairable/-friendly Design; Supply of Power for different Purposes (e.g. heating and cooling system, and provision of information) during the stop of the bus</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>INFRASTRUCTURE</strong></td>
<td>- Refuel. infrastructure: own refueling station</td>
<td>close to the Vehicle Depot; not interested in an own refueling station; wide-spread refueling infrastructure</td>
<td>wide-spread refueling infrastructure</td>
</tr>
<tr>
<td></td>
<td>- Service intervals (see also driving range): daily or every second day</td>
<td>every third day</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Refueling time: 3-4 minutes</td>
<td>2-3 minutes</td>
<td>3-5 minutes</td>
</tr>
<tr>
<td></td>
<td>- Refuel. convenience: easy to handle at the bus depot</td>
<td>Do-It-Yourself-Station</td>
<td>Do-It-Yourself-Station</td>
</tr>
<tr>
<td><strong>ACCEPTANCE</strong></td>
<td>Acceptance by Customer (Passenger) and Society</td>
<td>Acceptance by Customer of the Hermes Versand Service and Society</td>
<td>Acceptance by Customer and Society</td>
</tr>
<tr>
<td><strong>LIFE-CYCLE-COST</strong></td>
<td>It is assumed that the public transportation companies will accepted higher life-cycle cost (up to 10 % of additional costs compared to diesel) provided that the societal-driven and legal requirements can be fulfilled</td>
<td>It is assumed that higher expenses will be accepted (up to 5 % of additional costs compared to diesel) provided that the societal-driven can be fulfilled resulting in an increasing image of the company</td>
<td>It is assumed that higher expenses will only be accepted if the societal-driven can be fulfilled and the increase of the total life-cycle cost will not exceed the expenses of conventional technologies (gasoline and diesel) by more than 2,5 %</td>
</tr>
</tbody>
</table>

Tab. A.IV.5: Customer Requirements
Appendix V: Scenarios - Figures

Figure A.V.1: Switch to Hydrogen: Scenario "Decrease of the Green Tax in the Public Transport Sector"

Figure A.V.2: The Figure illustrates both the total production cost (Pf per km) of diesel and hydrogen (based on different energy sources) and the action plan for the implementation and market penetration of the hydrogen propulsion system in the field of "City Buses" (black colored line) - Scenario "Decrease of the Green Tax in the Public Transport Sector"
Figure A.V.3: Elements of Costs (in Pf per km) - Scenario "Business as usual" - "City Buses"

Figure A.V.4: Elements of Costs (in Pf per km) - Scenario "Business as usual" - "Vans"

Figure A.V.5: Switch to Hydrogen: Scenario "Business as usual" - "Passenger Car" powered by LH2
Figure A.V.6: Implementation Obstacles of LH₂ Powered Passenger Cars - Scenario 1

Figure A.V.7: Switch to Hydrogen: Scenario 2 - "Passenger Car" powered by LH2

Figure A.V.8: Implementation Obstacles of LH₂ Powered Passenger Cars - Scenario 2
Figure A.V.9: Switch to Hydrogen - Scenario "Business as usual" - "City Buses"; Number of hydrogen powered City-Buses by the year 2012 (different scales compared to Figure 8.2)
Appendix VII: Algorithms/Calculations/Operations performed by STELLA

- “City Buses”

\[
CGH2\_Buses(t) = CGH2\_Buses(t - dt) + (\text{Demand}_\text{HPS} - \text{After}\_\text{Use}) \times dt
\]

\[
\text{INIT} \ CGH2\_Buses = 2
\]

\[
\text{TRANSIT TIME} = 12
\]

\[
\text{INFLOW LIMIT} = \text{INF}
\]

\[
\text{CAPACITY} = \text{INF}
\]

\[
\text{INFLOWS:}
\]
\[
\text{Demand}_\text{HPS} = \text{Total}\_\text{Level}\_\text{of}\_\text{Satisfaction} + \text{Field}\_\text{Test}
\]

\[
\text{OUTFLOWS:}
\]
\[
\text{After}\_\text{Use} = \text{CONVEYOR OUTFLOW}
\]

\[
\text{Diesel\_Buses}(t) = \text{Diesel\_Buses}(t - dt) + (\text{Demand}_\text{Diesel} - \text{After}\_\text{Use}\_\text{D}) \times dt
\]

\[
\text{INIT} \ \text{Diesel\_Buses} = 82000
\]

\[
\text{TRANSIT TIME} = 12
\]

\[
\text{INFLOW LIMIT} = \text{INF}
\]

\[
\text{CAPACITY} = \text{INF}
\]

\[
\text{INFLOWS:}
\]
\[
\text{Demand}_\text{Diesel} = 6850 - \text{Demand}_\text{HPS}
\]

\[
\text{OUTFLOWS:}
\]
\[
\text{After}\_\text{Use}\_\text{D} = \text{CONVEYOR OUTFLOW}
\]

\[
\text{Diesel\_Cost\_per\_liter}(t) = \text{Diesel\_Cost\_per\_liter}(t - dt) + (\text{price\_increase} - \text{Noname}\_\text{2}) \times dt
\]

\[
\text{INIT} \ \text{Diesel\_Cost\_per\_liter} = 110
\]

\[
\text{INFLOWS:}
\]
\[
\text{price\_increase} = \text{Diesel\_Cost\_per\_liter} \times 1.01
\]

\[
\text{OUTFLOWS:}
\]
\[
\text{Noname}\_\text{2} = \text{Diesel\_Cost\_per\_liter}
\]
\[
\text{Green\_Tax\_per\_km}(t) = \text{Green\_Tax\_per\_km}(t - dt) + (\text{Increasing\_Rate}) \times dt
\]

\[
\text{INIT} \ \text{Green\_Tax\_per\_km} = 0
\]

\[
\text{INFLOWS:}
\]
\[
\text{Increasing\_Rate} = (\text{Green\_Tax\_per\_liter}/10) \times 4.5
\]

\[
\text{Additional\_Cost\_DM} = (\text{HPS\_engine\_Cost} \times 1.8 \times 59) / 100 - (\text{Diesel\_Engine\_Cost} \times 59 \times 1.8) / 100
\]

\[
\text{additional\_cost\_per\_year\_in\_DM} = (\text{HPS\_Cost\_per\_km}\_\text{Diesel\_Cost\_per\_km}) / 100 \times 250 \times 300
\]

\[
\text{ByProduct\_Fuel\_Cost} = \text{ByProduct\_Fuel\_Cost\_per\_kwh} \times 2.4
\]

\[
\text{ByProduct\_PF\_km} = \text{ByProduct\_Fuel\_Cost\_per\_kwh} + \text{Taxes\_per\_km}
\]

\[
\text{By\_Product\_Fuel\_Cost\_per\_kwh} = 27
\]

\[
\text{cost\_of\_diesel\_per\_year} = (\text{Diesel\_Cost\_per\_km}/10) \times 4.5
\]

\[
\text{Diesel\_Cost\_per\_km} = \text{Engine\_Cost\_Diesel\_per\_km} + \text{Diesel\_PF\_per\_km} + \text{Motor\_Vehicle\_Tax\_per\_km}
\]

\[
\text{Diesel\_Engine\_Cost} = 3000
\]

\[
\text{Diesel\_Fuel\_Cost\_per\_liter} = \text{Diesel\_PF\_per\_km}/10
\]

\[
\text{Diesel\_PF\_per\_km} = \text{Green\_Tax\_per\_km} \times \text{Diesel\_Cost}
\]

\[
\text{Electricity\_PF\_km} = \text{Electricity\_Fuel\_Cost} + \text{Taxes\_per\_km}
\]
Electricity_Fuel_Cost = Electricity_Pf_per_kwh*2.4
Engine_Cost_Diesel_per_km = ((Diesel_Engine_Cost*1.8*260)*1.04^12)/(250*300*12)
Engine_Cost_Hydrogen_per_km = ((HPS_Engine_Cost*1.8*260)*1.04^12)/(250*300*12)
HPS_Cost_per_km = HPS_Fuel_Cost_km+Engine_Cost_Hydrogen_per_km+Motor_Vehicle_Tax_per_km_2
HPS_Fuel_Cost_km = Strategy
Hydro_per_km = Hydro_Pf_per_kwh*2.4
Motor_Vehicle_Tax = 130000
Motor_Vehicle_Tax_2 = 130000/2
Motor_Vehicle_Tax_per_km = (Motor_Vehicle_Tax)/(250*300)
Motor_Vehicle_Tax_per_km_2 = ((Motor_Vehicle_Tax_2)/(250*300))*0
NonRenewable_per_km = IF((ByProduct_Pf_km)<(Electricity_Pf_km))AND(CGH2_Buses<12000)THEN(ByProduct_Pf_km)ELSE(Electricity_Pf_km)
No_of_Buses = CGH2_Buses+Diesel_Buses
Relative_Costs = (HPS_Cost_per_km*100)/Diesel_Cost_per_km
Renewable_Pf_km = (0.7*(Hydro_per_km+Tax))+(0.3*(Wind_Pf_per_km+Tax))
Strategy = IF((Renewable_Pf_km)<(NonRenewable_per_km))OR((Renewable_Pf_km)<(Diesel_Pf_per_km*1.05))THEN(Renewable_Pf_km)ELSE(NonRenewable_per_km)
Tax = Taxes_per_km*0
Taxes_Hydrogen = 0
Taxes_per_km = (Tax_per_kwh*Taxes_Hydrogen/100)*2.4
Tax_per_kwh = 7.15
Total_Level_of_Satisfaction = IF(Customer_Requirement<90)THEN(2)ELSE(Level_of_Satisfaction_Cost)
Wind_Pf_per_km = Wind_Pf_per_kwh*2.4
Customer_Requirement = GRAPH(TIME)
Electricity_Pf_per_kWh = GRAPH(TIME)
Field_Test = GRAPH(TIME)
(1999, 0.00), (2000, 4.00), (2001, 6.00), (2002, 8.00), (2003, 10.0), (2005, 0.00), (2006, 0.00), (2007, 0.00), (2008, 0.00), (2009, 0.00), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2016, 0.00), (2017, 0.00), (2018, 0.00), (2019, 0.00), (2020, 0.00)
Green_tax_per_liter = GRAPH(TIME)
(1999, 0.00), (2000, 6.00), (2001, 6.00), (2002, 6.00), (2003, 6.00), (2004, 12.0), (2005, 12.0), (2006, 12.0), (2007, 12.0), (2008, 12.0), (2010, 12.0), (2011, 0.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2015, 0.00), (2016, 0.00), (2017, 0.00), (2018, 0.00), (2019, 0.00), (2020, 0.00)
HPS_Engine_Cost = GRAPH(TIME)
Hydro_Pf_per_kWh = GRAPH(TIME)
Level_of_Satisfaction_Cost = GRAPH(Relative_Costs)
(99.0, 6850), (100, 6850), (101, 6850), (102, 6850), (103, 6850), (105, 6850), (106, 6850), (107, 6850), (108, 6850), (109, 6850), (110, 6850), (111, 3500), (112, 100), (113, 10.0), (114, 10.0), (116, 10.0), (117, 10.0), (118, 10.0), (119, 10.0), (120, 10.0)
Wind_Pf_per_kWh = GRAPH(TIME)
CGH2_Vans(t) = CGH2_Vans(t - dt) + (Demand_HPS - After_Use) * dt

INIT CGH2_Vans = 0

TRANSIT TIME = 3
INFLOW LIMIT = INF
CAPACITY = INF

INFLOWS:
Demand_HPS = Total_Level_of_Satisfaction + Field_Test

OUTFLOWS:
After_Use = CONVEYOR OUTFLOW

Diesel_Cost_per_liter(t) = Diesel_Cost_per_liter(t - dt) + (price_increase - Noname_2) * dt

INIT Diesel_Cost_per_liter = 115

INFLOWS:
price_increase = Diesel_Cost_per_liter* 1.01

OUTFLOWS:
Noname_2 = Diesel_Cost_per_liter

Diesel_Vans(t) = Diesel_Vans(t - dt) + (Demand_Diesel - After_Use_D) * dt

INIT Diesel_Vans = 1800

TRANSIT TIME = 3
INFLOW LIMIT = INF
CAPACITY = INF

INFLOWS:
Demand_Diesel = 600 - Demand_HPS

OUTFLOWS:
After_Use_D = CONVEYOR OUTFLOW

Green_Tax_per_km(t) = Green_Tax_per_km(t - dt) + (Increasing_Rate) * dt

INIT Green_Tax_per_km = 0

INFLOWS:
Increasing_Rate = (Green_Tax_per_km/10)*4.5

Additional_Cost_DM = (HPS_engine_Cost*1.8*59)/100 - (MVT_per_year*59*1.8)/100
additional_cost_per_year_in_DM = cost_of_hydrogen_per_year - cost_of_diesel_per_year

ByProduct_Fuel_Cost = By_Product_Fuel_Cost_per_kwh*0.7

ByProduct_PF_km = ByProduct_Fuel_Cost + Taxes_per_km

By/Product_Fuel_Cost_per_kwh = 27

cost_of_diesel_per_year = (Diesel_PF_km*280*200)/100

cost_of_hydrogen_per_year = ((HPS_PF_km*280*200)/100)

Depots = (CGH2_Vans)/28.125 + 1

Diesel_Cost = ((Diesel_Cost_per_liter/10)*1.2)

Diesel_Engine_Cost = 3000

Diesel_Fuel_Cost_per_liter = Diesel_PF_km*4.5*10

Diesel_PF_km = Engine_Cost_Diesel_per_km + Fuel_PF_km + Motor_Vehicle_Tax_per_km

Electricity_PF_km = Electricity_Fuel_Cost + Taxes_per_km

Electricity_Fuel_Cost = Electricity_PF_per_kwh*0.7

Engine_Cost_Diesel_per_km = ((Diesel_Engine_Cost*1.8*58)*1.04/6)/(200*280*6)

Engine_Cost_H2_per_km = ((HPS_engine_Cost*1.8*58)*1.04/6)/(200*280*6)
Fuel_Pf_km = Green_Tax_per_km+Diesel_Cost
HPS_Fuel_Cost_per_km = Strategy
HPS_Pf_km = HPS_Fuel_Cost_per_km+Engine_Cost_H2_per_km+Motor_Vehicle_Tax_per_km_2
Hydro_Pf_km = Hydro_Pf_per_kwh*0.7
Motor_Vehicle_Tax = MVT_per_year*18
Motor_Vehicle_Tax_2 = 1420/2
Motor_Vehicle_Tax_per_km = (Motor_Vehicle_Tax*6)/(200*280*6)
Motor_Vehicle_Tax_per_km_2 = (Motor_Vehicle_Tax_2*6)/(200*280*6)
NonRenewable_per_km = IF( (ByProduct_Pf_km)<(Electricity_Pf_km))AND(CGH2_Vans<12000 )THEN(ByProduct_Pf_km)ELSE(Electricity_Pf_km)
No_of_Vans = CGH2_Vans+Diesel_Vans
Relative_Costs = (HPS_PCkrn* 100)/DieseLPCkrn
Renewable_PCkrn = (0.7*(Hydro_PCkrn+Tax))+(0.3*(Wind_PCkrn+Tax))
Service_Stations = Depots*2
Strategy = IF( (Renewable_PCkrn)<(NonRenewable_per_km))OR( (Renewable_PCkrn)<(Fuel_Pf_km*1.005)) THEN(Renewable_PCkrn) ELSE(NonRenewable_PCkrn)
Tax = Taxes_per_km*0
Taxes_Hydrogen = 0
Taxes_per_km = (Tax_per_kwh*Taxes_Hydrogen/100)*0.7
Tax_per_kwh = 7.15
Total_Level_of_Satisfaction = IF(Customer_Requirement<90 )THEN(2 )ELSE( Level_of_Satisfaction_Cost)
Wind_Pf_km = Wind_Pf_per_kwh*0.7
Customer_Requirement = GRAPH(Relative_Costs)
Electricity_Pf_per_kWh = GRAPH(Time)
Field_Test = GRAPH(Time)
(1999, 0.00), (2000, 0.00), (2001, 2.00), (2002, 2.00), (2003, 2.00), (2005, 0.00), (2006, 0.00), (2007, 0.00), (2008, 0.00), (2009, 0.00), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2016, 0.00), (2017, 0.00), (2018, 0.00), (2019, 0.00), (2020, 0.00)
Green_Tax_per_liter = GRAPH(Time)
(1999, 0.00), (2000, 0.00), (2001, 6.00), (2002, 6.00), (2003, 6.00), (2005, 0.00), (2006, 0.00), (2007, 0.00), (2008, 0.00), (2009, 0.00), (2010, 0.00), (2011, 0.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2016, 0.00), (2017, 0.00), (2018, 0.00), (2019, 0.00), (2020, 0.00)
HPS_Engine_Cost = GRAPH(Time)
Hydro_Pf_per_kwh = GRAPH(Time)
Level_of_Satisfaction_Cost = GRAPH(Relative_Costs)
(100, 600), (101, 600), (102, 600), (103, 200), (104, 25.0), (105, 10.0), (106, 5.0), (107, 2.0), (108, 2.0), (109, 2.0), (111, 2.0), (112, 0.0), (113, 0.0), (114, 0.0), (115, 0.0), (116, 0.0), (117, 0.0), (118, 0.0), (119, 0.0), (120, 0.0)
MVT_per_year = GRAPH(Time)
Wind_Pf_per_kwh = GRAPH(Time)
- "Passenger Cars"

\[
\text{CF}_\text{Cars}(t) = \text{CF}_\text{Cars}(t - \text{dt}) + (\text{Demand} - \text{After Use CF}) \times \text{dt}
\]

INIT \( \text{CF}_\text{Cars} = 41673787 \)

TRANSIT TIME = 12

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:
Demand = Total Demand - Demand HPS

OUTFLOWS:
After Use CF = CONVEYOR OUTFLOW

\[
\text{CF\_Cost\_per\_liter}(t) = \text{CF\_Cost\_per\_liter}(t - \text{dt}) + (\text{price\_increase} - \text{Noname\_2}) \times \text{dt}
\]

INIT \( \text{CF\_Cost\_per\_liter} = 175 \)

INFLOWS:
price\_increase = \( \text{CF\_Cost\_per\_liter} \times 1.01 \)

OUTFLOWS:
Noname\_2 = \( \text{CF\_Cost\_per\_liter} \)

\[
\text{CGH2\_Cars}(t) = \text{CGH2\_Cars}(t - \text{dt}) + (\text{Demand HPS} - \text{After Use}) \times \text{dt}
\]

INIT \( \text{CGH2\_Cars} = 0 \)

TRANSIT TIME = 12

INFLOW LIMIT = INF

CAPACITY = INF

INFLOWS:
Demand HPS = Service Stations

OUTFLOWS:
After Use = CONVEYOR OUTFLOW

\[
\text{Green\_Tax\_per\_km}(t) = \text{Green\_Tax\_per\_km}(t - \text{dt}) + (\text{Increasing\_Rate}) \times \text{dt}
\]

INIT \( \text{Green\_Tax\_per\_km} = 0 \)

INFLOWS:
Increasing\_Rate = (\( \text{Green\_Tax\_per\_liter}/10\))\times 4.5

\[
\text{No\_of\_Service\_Station}(t) = \text{No\_of\_Service\_Station}(t - \text{dt}) + (\text{New\_Service\_Stations}) \times \text{dt}
\]

INIT \( \text{No\_of\_Service\_Station} = 2 \)

INFLOWS:
New\_Service\_Stations = Push\_Service\_Stations + (16700\times\text{Pull\_Service\_Stations}/100)

Additional\_Cost\_of\_Investment = \(((\text{HPS\_engine\_Cost}\times 1.859)\times 1.04^{12})/100) - (((\text{CF\_Engine\_Cost}\times 59^* 1.8)\times 1.04^{12})/100)

additional\_cost\_per\_year = \(((\text{HPS\_Fuel\_Cost\_per\_km-CF\_Fuel\_Cost\_per\_km})^250000)/12)/100

Additional\_DM\_Running\_Cost = (\text{Annual\_Running\_Cost-CF\_annual\_running\_cost})/100

Annual\_Running\_Cost = ((\text{HPS\_Fuel\_Cost\_per\_km+MVT\_per\_km\_Hydrogen})\times 250000)/12

\text{CF\_annual\_running\_cost} = ((\text{CF\_Cost\_per\_km+MVT\_per\_km})\times 250000)/12

\text{CF\_Cost} = ((\text{CF\_Cost\_per\_liter}/10)^*0.7)

\text{CF\_Cost\_per\_km} = \text{Green\_Tax\_per\_km+CF\_Cost}

\text{CF\_cost\_per\_year} = ((\text{CF\_Fuel\_Cost\_per\_km}^250000)/12)/100

\text{CF\_Engine\_Cost} = 3000

\text{CF\_Fuel\_Cost\_per\_liter} = \text{CF\_Cost\_per\_km}/4.5\times 10
CF_Pf_per_km = Engine_Cost_CF_per_km + CF_Cost_per_km + MVT_per_km
Cost_of_Investment_per_year_DM = Additional_Cost_of_Investment/12
Cost_of_Liquidation_per_km = 12*0.35
CRequirements = IF(Consequence_CR<95)THEN(0)ELSE(Total_Demand)
Driving_Range = (CRequirements*Consequence_DR)/100
Electricity_Pf_per_km = Electricity_Fuel_Cost + Taxes_per_km
Electricity_Fuel_Cost = Electricity_Pf_per_kWh*0.35
Engine_Cost_CF_per_km = (CF_Engine_Cost*1.8*59)*((1.04)^12)/(250000)
Engine_Cost_Hydrogen_per_km = (Engine_Cost_Hydrogen*1.8*59)*((1.04)^12)/(250000)
HPS_cost_per_year = ((HPS_cost_per_kWh*250000)/12)/100
HPS_Fuel_Cost_per_km = Strategy + Cost_of_Liquidation_per_km
HPS_Pf_per_km = HPS_Fuel_Cost_per_km + Engine_Cost_Hydrogen_per_km + MVT_per_km_Hydrogen
Hydro_Pf_per_km = Hydro_Pf_per_kWh*0.35
Lifecycle_Pf_per_km = (Driving_Range*Consequence_MC)/100
Miscalculation = (Lifecycle_Cost*Consequence_MC_2)/100
Miscalculation_Customer = (Cost_of_Investment_per_year_DM*1)+(Additional_DM_Running_Cost*0.5)
Miscalculation_in_% = (Miscalculation_Customer*CF_cost_per_year)/100
MVT_per_km_Hydrogen = ((Motor_Vehicle_Tax*14*12)-600)/250000
NonRenewable_per_km = Electricity_Pf_per_km
No_of_vehicles = CGH2_Cars + CF_Cars
Relative_Costs = (HPS_Pf_per_km*100)/CF_Pf_per_km
Renewable_Pf_per_km = (0.7*(Hydro_Pf_per_km+Tax))+(0.3*(Wind_Pf_per_km+Tax))
Service_Stations = (Miscalculation*Consequence_Service)/100
Strategy = IF((Renewable_Pf_per_km)<(NonRenewable_per_km))OR((Renewable_Pf_per_km)<(CF_Cost_per_km*1.01)) THEN(Renewable_Pf_per_km)ELSE(NonRenewable_per_km)
Tax = Taxes_per_km*1
Taxes_Hydrogen = 0
Taxes_per_km = (Tax_per_kWh*Taxes_Hydrogen/100)*0.35
Tax_per_kWh = 7.15
Total_Demand = After_Use_CF+New_Demand+After_Use
Wind_Pf_per_km = Wind_Pf_per_kWh*0.35
Consequence_CR = GRAPH(TIME)
(1999, 70.0), (2000, 72.1), (2001, 74.8), (2002, 80.9), (2003, 90.8), (2005, 100), (2006, 100), (2007, 100),
(2008, 100), (2009, 100), (2010, 100), (2011, 100), (2012, 100), (2013, 100), (2014, 100), (2016, 100), (2017, 100),
(2018, 100), (2019, 100), (2020, 100)
Consequence_DR = GRAPH(Liquid_H2)
(0.00, 0.00), (54.2, 0.00), (108, 0.00), (163, 0.00), (217, 0.00), (271, 0.00), (325, 0.00), (379, 0.00), (433, 0.5),
(488, 5.00), (542, 25.0), (596, 70.0), (650, 100)
Consequence_MC = GRAPH(Relative_Costs)
(99.0, 100), (100, 100), (101, 90.0), (102, 75.0), (103, 25.0), (104, 5.00), (105, 1.00), (106, 0.5), (107, 0.25),
(108, 0.125), (109, 0.05), (110, 0.05), (111, 0.025), (112, 0.01), (113, 0.00), (114, 0.00), (115, 0.00)
Consequence_MC_2 = GRAPH(Miscalculation_in_%)
(99.0, 100), (100, 100), (101, 90.0), (102, 75.0), (103, 25.0), (104, 5.00), (105, 1.00), (106, 0.5), (107, 0.25),
(108, 0.125), (109, 0.05), (110, 0.05), (111, 0.025), (112, 0.01), (113, 0.00), (114, 0.00), (115, 0.00)
Consequence_Service = GRAPH(No_of_Service_Station)
(0.00, 0.00), (1670, 2.50), (3340, 10.0), (5010, 20.0), (6680, 30.0), (8350, 60.0), (10020, 70.0), (11690, 80.0),
(13360, 90.0), (15030, 100), (16700, 100)
Electricity_Pf_per_kWh = GRAPH(TIME)
(2007, 35.0), (2008, 34.8), (2010, 34.6), (2011, 34.4), (2012, 34.2), (2013, 34.0), (2014, 33.8), (2015, 33.6),
(2016, 33.4), (2017, 33.2), (2018, 33.0), (2019, 32.8), (2020, 32.6)
Gaseous_H2 = GRAPH(TIME)
(2018, 650), (2019, 650), (2020, 650)
Green_Tax_per_liter = GRAPH(TIME)
(1999, 0.00), (2000, 0.00), (2001, 0.00), (2002, 0.00), (2003, 6.00), (2005, 8.00), (2006, 8.00), (2007, 8.00),
(2008, 8.00), (2009, 8.00), (2010, 8.00), (2011, 8.00), (2012, 0.00), (2013, 0.00), (2014, 0.00), (2016, 0.00),
(2017, 0.00), (2018, 0.00), (2019, 0.00), (2020, 0.00)
HPS_engine_Cost = GRAPH(Time)

Hydro_Pf_per_kwh = GRAPH(Time)

Liquid_H2 = GRAPH(Time)

Motor_Vehicle_Tax = GRAPH(Time)

New_Demand = GRAPH(Time)

Pull_Service_Stations = GRAPH(CGH2_Cars)
(0.00, 0.00), (5.1e+006, 25.0), (1e+007, 40.0), (1.5e+007, 60.0), (2e+007, 70.0), (2.6e+007, 90.0), (3.1e+007, 100), (3.6e+007, 100), (4.1e+007, 100), (4.6e+007, 100), (5.1e+007, 100)

Push_Service_Stations = GRAPH(Time)
(1999, 0.0), (2000, 0.0), (2001, 0.0), (2002, 0.0), (2003, 0.0), (2004, 0.0), (2005, 0.0), (2006, 0.0), (2007, 0.0), (2008, 4500), (2010, 3500), (2011, 0.0), (2012, 0.0), (2013, 0.0), (2014, 0.0), (2015, 0.0), (2016, 0.0), (2017, 0.0), (2018, 0.0), (2019, 0.0), (2020, 0.0)

Wind_Pf_per_kwh = GRAPH(Time)