PEM FUEL CELLS IN STATIONARY AND MOBILE APPLICATIONS
Pathways to Commercialization

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1. **Situation of Local and Global Emissions**

   The number of world citizens living in metropolitan centers will have sharply increased by the year 2015. Then some 500 urban areas will have more than 1 million inhabitants, as well as more than 30 agglomerations thereof will be populated by more than 8 million inhabitants. In the year 2025 already 2/3 of the world population will live in urban agglomerations. These densely populated areas will need clean energy, transport and water services.

   All these services require provision of energy sources, their conversion into a suitable form or carrier and their supply to the consumer. All these steps are related with certain efficiencies and therefore losses, which in the case of fossil sources inevitably lead to emissions. Among these emissions are locally and globally relevant ones. In confined urban areas local emissions such as carbon monoxide, hydrocarbons, sulfur dioxide and nitrogen oxides are of importance since they influence the formation of smog. Of global significance are carbon dioxide, methane and certain nitrogen oxides.

   One of the main contributors to urban pollution is the transport sector. In cities like Athens, Los Angeles and Mexico City carbon monoxide emissions at almost 100% come from road vehicles whereas NO\(_x\)-emissions are caused by road transport at between 75% and 85%. Worldwide some 1.1 billion urban citizens are suffering from severe air pollution. The World Bank relates about 700,000 death cases to this situation. California has issued a very strict emission control legislation, especially for road vehicles. From 2010 on, 30% of all transit bus miles have to be driven with zero emission technologies, the remaining 70% with ultra low emission technologies. From 2003 on, 10% of all large volume sales passenger cars have to be zero emission vehicles.

   Conventional pollutants such as CO, HC, NO\(_x\), SO\(_2\), and PM can be treated with end-of-pipe technologies such as catalytic converters and particle traps, sometimes rather costly measures. CO\(_2\) on the other hand cannot be extracted onboard vehicles with reasonable efforts. In order to come to ultra low emission vehicles or zero emission vehicles hydrogen is ideally suited. Hydrogen combustion in internal combustion engines leads only to minor NO\(_x\)-emission values whereas it avoids all other pollutants. Hydrogen use in proton exchange membrane fuel cell (PEMFC) propulsion systems causes no emissions at all. In both cases a CO\(_2\)-free fuel supply is feasible. Under these circumstances hydrogen conversion technologies seem to have a high development potential and thus a bright perspective for enabling clean energy and transportation services.

2. **Availability of Easy to Recover Mineral Oil Resources**

   The content of this chapter is adapted from [3]:

   For a long time man has not seriously considered the question of how large the total worldwide mineral oil reserves are, and how long these will last. Then after a long period only the study "World Oil Supply 1920-2050" appearing in 1995 [4], provided a substantiated independent analysis of the problem of oil reserves. This work was based on the largest independent data base with data on more than 10,000 oil fields - that of Petroconsultants in Geneva - as well as on the decades of experience of the authors in analyzing oil fields. The study arrives at the conclusion that the earlier estimates of Hubbert [an American geologist; he was the first who pointed out the fact that the exploitation over time of each oil well follows the shape of a bell curve; the production rises over the years, reaches its maximum when about half the oil has been extracted, and then drops continuously again. The most important work of Hubbert was that he turned attention to the question of when the production in a certain oil producing area, or even worldwide, would reach its maximum - this question is just as interesting as the question for how many years the remaining oil will last. He also predicted in 1956 that the American oil output would reach its maximum at the beginning of the 70's – and he was correct], and the assessment of the "Global 2000" report [In this report it was already found that the percentage of success in finding new oil
fields is decreasing, and that the mineral oil production is assumed to reach its peak at the end of the millennium. The study, conducted in 1980, came to the conclusion that a total of 2,100 billion barrels of ultimately recoverable oil is available on Earth, a statement that, in the light of present knowledge, lies at the upper limit], were surprisingly exact. In contrast to these earlier studies forecasts today can be supported by considerably better statistical data.

Looking at the time pattern in the discovery of oil reserves is also revealing. All really large deposits were already discovered decades ago: 80% of the oil produced today originates from wells that are known for 30 years or more. The maximum of new oil discoveries was reached in the 1960's. Despite intensive exploration efforts after the two oil crises, new finds are becoming less and less. This is also in no way surprising, because the geological factors and relationships that have led to the formation of oil in the history of the Earth are now well established and well understood. We therefore know where to look for oil, and we know where there is nothing to be found. It is therefore obvious that the larger deposits have already been found early with simple methods and that later in time the ever smaller ones were found. The sum curve of all reserves discovered so far is asymptotically approaching a limit.

So what is briefly our knowledge so far? The most reliable numbers originate from Petroconsultants, as of 1996 [5]:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Production to date</td>
<td>784 billion barrels</td>
</tr>
<tr>
<td>Known reserves</td>
<td>836 billion barrels</td>
</tr>
<tr>
<td>Probably yet to find</td>
<td>180 billion barrels</td>
</tr>
<tr>
<td>Total amount of</td>
<td></td>
</tr>
<tr>
<td>ultimately recoverable oil in the world</td>
<td>1800 billion barrels</td>
</tr>
</tbody>
</table>

These numbers show that we have produced almost half the mineral oil of the world already. In the years around the turn of this millennium the so-called "mid-depletion point" will be reached, i.e. the point in time at which half of the extractable oil will be actually extracted [see figure 1]. Sometime in the next few years the annual oil production, which reached about 23 billion barrels in 1996, will begin to decline.

In addition doubts are appropriate as to whether statistics about the global oil reserves, handed out and publicized annually, really correspond with reality.

It must be visualized here how these statistics are made up. The basis for these statistics is not original information provided in a scientific manner subject to objective analysis and verification but rather each oil producing country in the world transmits his own oil reserve data annually to the "Oil and Gas Journal". This journal publishes the information without comment and without checking. All other publicly accessible statistics, such as the "BP Statistical Review of World Energy", statistics published by Shell, Esso etc., also use these same data without comment. The impression is thus given that these are all independent analyses, which is not the case. The information from the German Federal Agency for Geo-Science and Raw Materials, or the statistics issued by the German Federal Ministry for Economic Affairs, are also based on these same publications. Apart from Petroconsultants nobody has access to original and proprietary data the scope of which considerably exceeds the area of experience of the own country or the individual oil company.

At this point it is time to discuss in more detail the concept of the (static) "reserves to production ratio" ("for how many years will the still available oil last at today's consumption rates"). This parameter was already used by the Club of Rome. It is the most prominent figure of all statistical publications and finds more and more attention. The handling of this parameter in public debates is, to a certain extent, remarkable. Various lines of argument that are quite contrasting stand next to each other.
One time it is said that the "reserves to production ratio" has remained at 30 or 40 years for the last 40 years - that is to say enough new deposits were obviously continuously found to make up for current consumption. The finiteness of oil is therefore obviously not a practical problem. The faulty estimates of the past of the "reserves to production ratio" simply show that the real reserves are much larger than stated by this figure. Only if this would not be the case anymore however one would have to be worried. But this simple view ignores that most of the reported "reserve growth" is due to suspicious reserve reevaluation of already existing fields in the OPEC countries. Between 1985 and 1990 this "growth" added 300 billion barrels of oil reserves, about 1/3 of the total reserves.

Lately, one hears on the other hand, that we need not to have any fears about the availability of mineral oil, because supply is secured after all for the next 40 years. One time therefore, 40 years are much too short a time, and another time a comfortably long time.

The concept of the "reserves to production ratio" as such is rather misleading for a number of reasons. For one, and that we have already tried to explain, the production does not stay at a constant level over time, and then suddenly comes to an end when the last drop has been extracted. But production rather follows a bell shaped curve. Secondly a constant consumption of oil over time is assumed in the concept of the "reserves to production ratio". The world's consumption of oil is growing however. In so far the "reserves to production ratio" overestimates the time oil will be available.

Another aspect is that after passing the "mid-depletion point" of a production area, the "reserves to production ratio" becomes increasingly misleading. This can be easily demonstrated using the example of the oil production in Germany. After all we had a "reserves to production ratio" of 11 years at the time of peak production in 1968. Today, with a production level of only 40% of peak production and much less remaining reserves, the "reserves to production ratio" has increased to 18 years.

It is also frequently suggested that one can defer the problem of finiteness by applying advanced technologies. That is obviously correct in principle, but is significantly overestimated in its effect. By using advanced technologies oil fields can be exploited to a - probably not all that much - greater extent for example, but this only at considerable financial and technical expense. The principal effect is that the existing deposits are being exhausted even faster. Here again the example of Germany: the use of all the modern pumping technology has hardly altered the overall shape of the production curve over time. And generally one has to be aware of the fact that the size of reserves cannot be increased by however potent technologies. Technology and reserves have nothing to do with each other after all; or to say it precisely: we will not run out of oil, in principle – there are still large amounts of non-conventional oil shales, oil sands, orimulsion, etc.

But on the other hand:

1. Conventional oil production will peak very soon (probably within 5 to 10 years)
2. Non-conventional oil will not be able to fill that gap – production methods are expensive, environmentally harmful and by no means growth will be as fast as for conventional oil production
3. Therefore, certainly we will run out of cheap and easy to recover oil very soon [see figure 2]
3. **Historical Development of Fuel Cell Technology**

The fuel cell principle was discovered by the Englishman William Robert Grove in 1839. He described a "galvanic gas battery" which through "cold combustion" of hydrogen and oxygen should generate electric current with a theoretical efficiency of almost 100%. One of the first to recognize the importance of H2/O2 fuel cells for electricity generation was Westphal in 1880.

In 1894, Ostwald proposed to use a process of combining C and O2. The successful realization failed due to the high operating temperatures of 1000°C and the related materials problems. Thereafter most research efforts focused on the H2/O2-reaction which could be controlled easier.

The technical development of fuel cells started shortly after World War II when Francis T. Bacon of Cambridge, England, successfully developed a high pressure cell. A functioning device was presented in 1954. Subsequently alkaline fuel cells (AFC) and acidic polymer membrane fuel cells (PEMFC) were developed for space programs (Gemini, Apollo, Spacelab). Due to acceptable high costs alkaline fuel cells where successful in space and military applications.

In the early 1970s the development of phosphoric acid fuel cells (PAFC), of high temperature molten carbonate (MCFC) and of solid oxide fuel cells (SOFC) started. All these developments at the beginning aimed at large-scale power plant applications up to several 100 MW. In the meantime, most development activities focus on dedicated power units either for electricity or for combined electricity and heat generation. ONSI in the USA has already delivered more than 100 units of its 200 kW PAFC cogeneration unit to clients in the US and all over the world for test trials. Commercialization is planned for 1998 at prices of 1,500 US$/kW. Much lower specific prices are not very likely to be achieved. MCFCs (ERC/MTU, Ansaldo, ECN, MC Power, IHI, Hitachi, MELCO, Tonen, etc.) and SOFCs (Westinghouse, Siemens, DaimlerChrysler, Sulzer, Ceramatec, MHI, ECN, Statoil, etc.) are presently leaving the laboratories and also entering into the first pilot applications. Commercialization will start between 2000 and 2005.

PEMFCs were not investigated with significant efforts before the late 1970s, early 1980s. These intensified activities, mainly by Ballard, Siemens, H Power, International Fuel Cells and several US universities and research centers, resulted in significantly improved membrane-electrode-assemblies (MEA). Therefore, weight and cost of the PEMFCs could be reduced drastically and their performance increased dramatically. This in turn, motivated several car and bus manufacturers (Ballard/New Flyer, DaimlerChrysler, Ford, GM/Opel, Honda, MAN, Mazda, Neoplan, Nissan, PSA, Renault, Toyota, Volvo) to consider PEMFCs seriously as an alternative propulsion system to the existing internal combustion engines. First commercial PEMFC systems of in the order of 1,000 US$/kW can be expected around the year 2001/2002, thus enabling their use in stationary applications and in some selected fleet vehicle programs.

4. **Fuel Cell - Design and Function**

Presently used thermal engines (e.g. gas turbines, gas motors) convert the energy contained in the fuel via thermal and mechanical energy into electrical energy (indirect electricity generation). The electrochemical energy conversion used in fuel cells converts the energy contained in the fuel directly into electricity (direct electricity generation).

Thermal engines are compared in their efficiency by the Carnot process \( \eta_c = 1 - T/T_0 \) which at a given ambient temperature gives higher efficiencies at higher process temperatures. Fuel cells on the other hand, are compared in their efficiency by the so-called reversible cell efficiency \( \eta_{FCEV} = \Delta G / \Delta H = (\Delta H - T \cdot \Delta S) / \Delta H = 1 - T \cdot \Delta S / \Delta H \). For methane the reversible cell efficiency is practically constant over temperature, whereas for hydrogen it is decreasing with increasing temperature. The cell efficiency thus depends more on the fuel type than it is the case for thermal engines.
The design and function of a fuel cell can most easily be explained by using the concept of the low temperature polymer membrane fuel cell [see figure 3], also called proton exchange membrane fuel cell (PEMFC).

The membrane acts as acidic electrolyte. The reactants - hydrogen and oxygen (from the air) - are fed continuously to the two electrodes. Hydrogen diffuses through the porous anode to the three phase boundary (catalytic surface/ electrolyte/ hydrogen) and there will be split into protons and electrons:

\[ \text{H}_2 \rightarrow 2 \text{H}^+ + 2 \text{e}^- \]

The hydrogen ion (H\(^+\)) on its way to the cathode passes through the polymer membrane, which is highly conductive for protons. At the same time the electrons flow to the cathode via an outer electric circuit. At the three phase boundary between cathode and electrolyte, the hydrogen ion together with the electrons of the outer electric circuit and the oxygen which has diffused through the porous cathode reacts to clean water:

\[ 2 \text{H}^+ + \frac{1}{2} \text{O}_2 + 2 \text{e}^- \rightarrow \text{H}_2\text{O} \]

The water resulting from this reaction will be extracted from the system by the excess air flow.

The two reactions result in the following summary reaction:

\[ \text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O} \]

Due to the surplus of electrons at the anode and the deficit of electrons at the cathode a potential difference between the two electrodes develops, i.e. a short circuit voltage of approx. 1.1 V can be measured. If a consumer is integrated into the circuit, the voltage drops to approx. 0.7 V. This voltage is maintained as long as sufficient amounts of hydrogen and oxygen are supplied to the anode and cathode respectively. In the case of fuel cells, other than for batteries, the electrodes practically do not or only very slightly change their properties over lifetime.

The key component of any fuel cell is the membrane-electrode-assembly (MEA). The electrolyte has to separate the feed gases enabling two partial reactions - oxidation and reduction - as well as to ensure the transport of the ions between the two electrodes. Thus the electrolyte shall be permeable for gases and be highly conductive for ions. Lyes and acids as well as solid materials and fusions with acidic or alkaline characteristics are suitable.

In order to produce efficient, light weight and longlife fuel cells a thorough knowledge of the fluidmechanical, catalytic and electrochemical processes occurring at the electrodes is essential. At the electrodes the conversion of the chemical energy contained in the fuel into electric current is realized, i.e. the mass flow of the fuel is converted into a flow of electric current which is linked to the electric current of the outer electric circuit and to the ion transport occurring through the electrolyte. Therefore, the electrodes must be permeable for all three acting species: gas molecules, ions and electrons. This requires the formation of a three phase reaction zone (electrolyte/ catalytic surface/ educt gas) which is characteristic for each fuel cell electrode. In order to ensure a large conversion rate, the three phase reaction zone and thus the electrode surface has to be as large as possible. Additionally, the optimization of the transport processes of the active species (gas molecules, ions and electrons) and a sufficiently high electrochemical boundary layer reaction velocity is of utmost importance. The reaction velocity in the boundary layers usually can be increased only by employing catalytic coatings. The lower the operating temperature of a fuel cell, the more important the catalytic acceleration of the reaction process. In the case of acidic electrolytes only noble metals such as platinum or ruthenium can be used as catalysts because less precious metals would be dissolved over time.

For achieving a technically suitable voltage level, single cells consisting of cathode, electrolyte and anode have to be assembled in series. Between the single cells so-called bipolar plates have to be integrated. These bipolar plates facilitate the gas supply to the electrodes and electrically connect the single cells. Usually single cells and bipolar plates are piled up one on the other in the form of sandwiches and fixed between two end plates. Such piles are called ‘fuel cell stacks’. In order to extract the reaction heat usually a certain number of
cooling plates are inserted into the stack. Some stack designs accomplish cooling within each bipolar plate and do not require separate cooling plates. The gas supply as well as the supply and removal of the cooling liquid is either accomplished through the end plates (serial, parallel or cascaded media circulation) or directly at the side of each single cell (parallel media circulation).

In principle fuel cells can convert all fluidic substances which can be oxidized. In practice exists quite a difference between hydrocarbon fuels and hydrogen. All fuel cells can convert hydrogen in the above described way directly. Fuel cells electrochemically converting hydrocarbon fuels directly are still in the laboratory stage. The difficulty in oxidizing hydrocarbons directly is related to their difficult oxidizability due to their inert chemical property which either requires very large active catalytic surfaces (e.g. direct methanol fuel cell DMFC) or very high reaction temperatures (MCFC: 650°C, SOFC: 800°C-1000°C).

Nevertheless, hydrocarbon fuels such as methanol, natural gas or synthesis gas can be used in today’s fuel cells indirectly, i.e. by employing a chemical reactor prior to entering the fuel cell. The hydrocarbon fuel is converted into a hydrogen rich synthesis gas via a water vapor reformer or a partial oxidizing burner and then is purified in a gas purification stage to clean hydrogen. Emissions of these processes usually are CO and CO₂. In the case of low temperature fuel cells too high CO-contents (i.e. > 10 ppm) are poisoning the Platinum catalyst and therefore have to be limited to below 10 ppm. In the case of medium temperature fuel cells (e.g. PAFC) the adsorption/desorption balance is shifted to desorption at increased temperature level thus allowing higher CO-contents of even some percent.

Fuel cell systems for small and medium scale stationary as well as for mobile applications are significantly more efficient in fuel utilization than internal combustion engines [see figures 4 and 5].

5. FUEL CELL TYPES AND THEIR FIELDS OF APPLICATION

Usually fuel cells are classified according to their operating temperatures into low, medium and high temperature fuel cells. Table 1 below gives an overview of the fuel cell technologies presently under development respectively on their way to commercialization.

<table>
<thead>
<tr>
<th>FUEL CELL TYPE</th>
<th>OPERATING TEMPERATURE [°C]</th>
<th>ELECTROLYTE</th>
<th>FUEL</th>
<th>OXIDATION MEDIA</th>
<th>TYPICAL UNIT SIZES [kWₑ]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline Fuel Cell (AFC)</td>
<td>70 - 100</td>
<td>alkaline lye</td>
<td>H₂</td>
<td>Oxygen</td>
<td>&lt;&lt; 100</td>
</tr>
<tr>
<td>Proton Exchange Membrane Fuel Cell (PEM)</td>
<td>50 - 100</td>
<td>Perfluorinated sulphonated polymer electrolyte</td>
<td>H₂ and reformed H₂</td>
<td>Oxygen from air</td>
<td>0,1 - 500</td>
</tr>
<tr>
<td>Phosphoric Acid Fuel Cell (PAFC)</td>
<td>160 - 210</td>
<td>Stabilized phosphoric acid</td>
<td>H₂ reformed from natural gas</td>
<td>Oxygen from air</td>
<td>5 - 200 (plants up to 5,000)</td>
</tr>
<tr>
<td>Molten Carbonate Fuel Cell (MCFC)</td>
<td>650</td>
<td>molten carbonate solution</td>
<td>H₂ and CO from internal reforming of natural gas or coal gas</td>
<td>Oxygen from air</td>
<td>800 - 2,000 (plants up to 100,000)</td>
</tr>
<tr>
<td>Solid Oxide Fuel Cell (SOFC)</td>
<td>800 – 1000</td>
<td>ceramic solid electrolyte</td>
<td>H₂ and CO from internal reforming of natural gas or coal gas</td>
<td>Oxygen from air</td>
<td>2.5 - 100,000</td>
</tr>
</tbody>
</table>
The most probable fields of application for the different fuel cell concepts are given in the following table 2:

<table>
<thead>
<tr>
<th>FUEL CELL TYPE</th>
<th>MOST LIKELY FIELDS OF APPLICATION</th>
<th>AVAILABILITY</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alkaline Fuel Cell (AFC)</td>
<td>Space applications; Special military applications</td>
<td>today</td>
</tr>
<tr>
<td>Proton Exchange Membrane Fuel Cell (PEM)</td>
<td>Stationary applications for direct hydrogen use</td>
<td>1999</td>
</tr>
<tr>
<td></td>
<td>Stationary applications for domestic power and heat production</td>
<td>2000/ 2001</td>
</tr>
<tr>
<td></td>
<td>Stationary applications for dedicated power (and heat) production</td>
<td>2002/ 2003</td>
</tr>
<tr>
<td></td>
<td>Mobile applications for buses, service vehicles</td>
<td>2001-2003</td>
</tr>
<tr>
<td></td>
<td>Mobile applications for railroad systems (streetcars, locomotives)</td>
<td>2003</td>
</tr>
<tr>
<td></td>
<td>Mobile applications for passenger cars</td>
<td>2005-2010</td>
</tr>
<tr>
<td>Phosphoric Acid Fuel Cell (PAFC)</td>
<td>Stationary applications for dedicated power (and heat) production</td>
<td>1998</td>
</tr>
<tr>
<td></td>
<td>Mobile applications</td>
<td>&gt; 2000</td>
</tr>
<tr>
<td>Molten Carbonate Fuel Cell (MCFC)</td>
<td>Stationary applications for combined power and vapor production</td>
<td>2001</td>
</tr>
<tr>
<td></td>
<td>Stationary applications for utility use</td>
<td>&gt; 2005</td>
</tr>
<tr>
<td>Solid Oxide Fuel Cell (SOFC)</td>
<td>Stationary applications for domestic heat (and power) production</td>
<td>2000</td>
</tr>
<tr>
<td></td>
<td>Stationary applications for commercial heat and power production</td>
<td>2001-2003</td>
</tr>
<tr>
<td></td>
<td>Stationary applications for utility use; Mobile applications for railroad systems</td>
<td>&gt; 2005</td>
</tr>
</tbody>
</table>

6. OVERVIEW OF SELECTED PEM FUEL CELL TECHNOLOGY COMPANIES AND DEMONSTRATION PROJECTS

6.1 Stationary applications

6.1.1 Technology Companies

AlliedSignal Aerospace

AlliedSignal Aerospace (ASA) of Torrance, USA, develops membranes, single cells and stacks for PEMFC. Furthermore, ASA develops monolithic SOFCs. ASA is partner in the Chrysler fuel cell program and responsible for stack and system development, for hydrogen storage and system integration. Goal of the program is the development of a 30 kW_e system.

Analytic Power Corp./ American Power Corp.

Analytic Power (AP) of Boston, MA, USA, is active in the field of PEM fuel cell stacks and systems and of autothermal-reformers. AP has a small manufacturing facility for its 3.5/10 kW_e prototype PEMFC stack. The PEMFC system is composed of two 1.75 kW_e stacks which are complemented with a battery booster in order to reach 10 kW_e for peak energy demand coverage. The total energy output (electric/ thermal) is 8 kW. [see figure 6] AP develops an autothermal reformer for PEMFC operation with Diesel fuel for the US Navy and for other fuels (natural gas, propane) in civil applications. The electric efficiency is presently at 30% (goal: 40%) and the total efficiency at 75% (goal: 85%). The estimated manufacturing price for the 3.5 kW_e / 4.5 kW_th system is US$ 4,000 (at 10,000 units per year) respectively US$ 3,500 (at 100,000 units per year). The installed system price then would sum up to US$ 5,000 per system. Electricity generation costs based on natural gas are estimated to be in the order of 7-10 cents_US$/ kWh_e. Market introduction is planned for 2003.

AP presently develops a low cost PEMFC concept which shall allow 25 kW_e systems which can be extended to 50 kW_e and which also can be throttled to 10 kW_e. The specific investment cost goals are 20 US$/ kW_e.

Avista Labs

Avista Corp. affiliate, Avista Labs, disclosed in April 1999 that it has selected Logan Industries, Inc., as its contract manufacturing partner for its introductory proton exchange membrane (PEM) fuel cell generators.
slated for field tests this spring. Under the terms of the one-year agreement, Logan Industries, Inc., will manufacture, assemble and test a minimum of 200 PEM fuel cell power units, with delivery of the first unit by May 31. Logan Industries, Inc., will also procure the raw materials and inventory required to manufacture the innovative Avista Labs fuel cell product.

The stack unit consists of a 720-watt subrack with twelve, 60-watt power modules and weighs approx. 43 kg. The unit is scalable to match a customer's specific load characteristics. Avista Labs' innovative fuel cell design overcomes the disadvantages of costly traditional designs based on stacked graphite plates by using low cost materials, minimal support systems (balance of plant), a highly modular design and a unique approach to water management. The unit operates at ambient pressure in a temperature range of -20°C - + 35°C, is convection cooled and is self humidified.

Ballard Power Systems Inc.

Ballard Power Systems Inc. of Burnaby, British Columbia, Canada, has developed PEM fuel cell demonstration units of 30 kW_e (hydrogen fueled) and 10 kW_e (natural gas fueled). The 10 kW_e PEMFC unit with compact natural gas reformer was the first integrated PEMFC unit to be operated with natural gas. This power plant provides the technical basis for an up-scaling to a 250 kW_e unit. Ballard prepares to start commercialization field testing of such 250 kW_e units with natural gas reformer together with utility partners (BEWAG, HEW, Preussen Electra, VEAG, EdF) by end of 1999 in Berlin, Germany [see figure 6]. High volume manufacturing and commercial sales shall commence by the year 2002. These manufacturing and marketing activities shall be performed with strategic partners, such as GPU International, an international power generation and distribution company active in deregulated electricity markets worldwide, and with Alstom. With Alstom of France, Alstom Ballard GmbH has been formed which will start manufacturing of PEMFC cogeneration systems in Dresden, Germany, very soon.

Furthermore, Ballard is very active in the field of mobile propulsion systems. For shortly after 2000 the introduction of a full size low floor transit bus by New Flyers with a net propulsion power of 205 kW_e is planned as a niche product. Small fleet trials take place in Chicago and Vancouver since 1998. Ballard delivers fuel cell systems to several car manufacturers, the most important client being DaimlerChrysler in Germany and Ford in the USA.

Daimler-Chrysler AG

DaimlerChrysler AG (DC) of Stuttgart, Germany, is active in the field of PEMFC stack and system development as well as in methanol reformer development. In 1993 DC signed a contract for cooperation with Ballard Power Systems for the joint development of a 25 kW_e stack for automotive applications. In a first stage - MB 180 BZ/ Necar I - DC used twelve 5 kW_e stacks with a specific weight/power ratio of 10 kg/kW_e (system: 21 kg/kW_e). The second stage in 1996 – V-cals/ Necar II - a specific weight/power ratio of 3 kg/kW_e (system: 6 kg/kW_e) could be realized in two 25 kW_e stack. The net power output of the fuel cell system was in the range of 40 kW_e. In 1997 DC presented the NEBUS, low floor bus with a net 190 kW PEMFC system, and the NECAR III, a A-class model with methanol onboard reforming and 50 kW_e propulsion power (only two seats). In 1999, DC presented the NECAR IV to the US-public, an A-class model with onboard LH2 storage, four seat, 450 km operating range, 145 km/h maximum velocity and drive-cycle tank to wheel efficiency of > 36%. Beginning of 2000, DC will present NECAR V, an A-class model with methanol onboard reforming (size reduced reformer unit) and four seats.

DC seems to have the most advanced technology of PEMFC systems and methanol reformers for automotive applications worldwide and pursues the development with large monetary and manpower efforts. Major efforts are presently invested in the investigation of mass producability of the PEMFC system and the methanol reformer. If all established goals will be fulfilled, mass production of PEMFC vehicles will be feasible after the turn of the century.
**DE NORA S.P.A.**

De Nora S.p.A. of Milano, Italy, is one of the leading manufacturers of modern chlorine-alkaline-electrolyzers with membrane technology and of water electrolyzers. Since 1991 De Nora is active in the development of proprietary PEM fuel cell MEA and stack technology. Since 1995 De Nora works also on systems integration of complete stationary PEMFC systems. De Nora plans to commercialize PEMFC systems of 15 to 20 kW_e directly fueled with by-product hydrogen from chlorine production by late 1999. In parallel, De Nora develops PEMFC units of 50 kW_e with an integrated natural gas reformer for commercial and domestic application which shall be commercialized by the year 2000. Specific prices of US$ 2,000/ kW_e,system are foreseen for hydrogen fueled systems by 1998 and about US$ 1,500/kW_e,system for natural gas fueled systems by 2000.

Additionally, De Nora develops an advanced cost effective high power density PEMFC unit for mobile applications to be delivered by 1999. This stack technology will have a specific weight of 4 kg/kW_e and thus an improvement factor of 2.5 compared with present technology or of 6.3 compared with the technology status of five years ago. These fuel cell stacks are used in car and bus demonstration projects by Renault, PSA Peugeot and MAN.

The major research activities of De Nora focus on low pressure electrodes (0.1-0.15 MPa), investigation on CO tolerant catalysts and low cost electrode manufacturing technologies.

**ENERGY PARTNERS**

Energy Partners (EP) of West Palm Beach, Florida, USA, is a manufacturer of PEM stacks and systems and of prototype fuel cell vehicles. EP has developed fuel cell stacks of 5.4 kW_e (1993), 12 kW_e (1996) and will develop stacks of approx. 19 kW_e in the future years [all figures refer to 780 cm² active cell area, 60 cells, approx. 47 V cell voltage at half power rating], whereas the platinum loadings decreased from 4 mg/cm² (1993) to 0.3 mg/cm² and will drop to 0.15 mg/cm² in the future. The respective operating pressures are 0.24 MPa (1993), 0.30 MPa and to be defined in the future (presumably lower). The specific weight of the stacks decreased from 19 kg/kW_e to 6.4 kg/kW_e and will decrease to 2.5 kg/kW_e. The first stacks were realized with DuPont’s Nafion membranes. The present stacks are realized with membranes from W.L. Gore. For the future stacks the membranes have still to be defined. A 7.5 kW_e PEMFC cogeneration system has been delivered to a technology center in Risa, Saxony, Germany. Commercial units of 1-10 kW_e are expected to enter the market by 2001.

**GLOBAL FUEL CELL CORPORATION (GFC)**

Southern States Power Co. (SSPC) has formed a joint venture with Anuvu, Inc., in 1998, in order to complete development and demonstration of an advanced PEM fuel cell that will be demonstrated in a series of fuel cell powered electric vehicle runs in California and other locations. This joint venture combines the fuel cell technology of Anuvu and the electric vehicle production capabilities of SSPC.

Global Fuel Cell Corporation is owned 50% by Anuvu and 50% by SSPC. SSPC has also completed an electric mini-van with a state of the art AC drive system that has a fully computerized monitoring system. A series of vehicle runs are planned over the next few months with the fuel cell using a variety of fuels including hydrogen, natural gas, propane, methanol & gasoline.

Anuvu fuel cells’ most important advantage is the lower costs and rapid timeline to enter into production. The GFC Carbon-X technology is sturdy and flexible and can rapidly be produced using standard low cost equipment. This, among others, has been achieved by focusing the design process on choosing materials that would be compatible with mass-production manufacturing techniques.

Much less volume is required for the GFC through the use of a proprietary process to manufacture very thin fuel cell plates with non-corrosive materials. This leads to a very compact, light-weight fuel cell. The bi-polar
plates are 2.5 mm thick, making them the most compact in the industry for high-powered cells. The weight is further reduced by use of a low-density material. This contributes to reducing manufacturing costs.

Thermal management is achieved in every cell through a proprietary cooling process for the fuel cell. This radically decreases thermal gradients in the cell and thus optimizes fuel cell performance. Humidity management is accomplished through the use of materials that prevent product water from forming an obstruction in any of the gas passages. This prevents both dying out and flooding of the cells. Humidity levels can be kept on the high end, without danger of damage from flooding.

GFC plans to bring 'Carbon-X' fuel cells into production by 2000. GFC intends to be one of the first companies to produce viable fuel cells for commercial vehicles and stationary fuel cell applications. GFC due to the mass-producible fuel cell design is convinced that is able to introduce commercial fuel cells into the commercial market years ahead of competitors' fuel cells at a much lower cost. GFC would then be in a position to sell competitively priced fuel cells to auto companies when Zero Emission Vehicle mandates go into effect in 2003 (60 – 140,000 vehicles).

**H Power Corp.**

H Power Corp. of Belleville, New Jersey, USA, presently manufactures two types of naturally aspirated PEM fuel cell systems. The so-called microsystems (50 W_e to 300 W_e) meant for battery replacement use bipolar plates from graphite and are manufactured entirely by H Power. Several hundreds are hand-manufactured at laboratory-scale per month. A semi-automated manufacturing will exist soon and shall lead to up to 10,000 units per month within one years' time. For larger fuel cell systems (2.5 to 50 kW_e) the bipolar plates will be manufactured according to the platelet concept providing three-dimensional channels. Single cells of 400 cm^2 area are under testing presently. First prototypes with this technology were delivered by end of 1997. H Power plans to manufacture and deliver to pilot clients the first ten prototypes of a 2.5 kW_e (10 kW_e,peak) total energy module system which provides its peak power via an integrated battery system and which generates its hydrogen via partial oxidizer from propane by end of 1999. The first 10 to 20 prototypes shall be sold to utilities for field testing at a price of US$ 65-100,000 per unit. The market will accept system prices of US$ 7,000 to US$ 10,000. At a production volume of 1,000 units per year, unit cost of US$ 5,000 shall be achievable.

This technology will form the basis for 2.5 to 50 kW_e units which shall also be employed in mobile applications. A first PEMFC prototype fueled with hydrogen produced with an underoxidized partial burner system from diesel fuel is presently conceived as propulsion unit for a pick-up truck and funded by DARPA. This propulsion concept will form the basis for a full size transit bus with a 100 kW_e PEMFC system fueled with Diesel and to be operated by SMUD (Sacramento Municipal District) by end of 1999.

**International Fuel Cells**

International Fuel Cells (IFC) of South Windsor, Connecticut, USA, is active in the development of PEM stacks and systems, PAFC systems and methanol reformers. IFC is an affiliate of UTC and active in fuel cell development since about 50 years. The most well know fuel cell activity of IFC is the PAFC commercialization program of its subsidiary ONSI (together with Toshiba). IFC has developed a 50 kW PEMFC for Ford Motor Co. [see figure 8]. IFC has proposed an innovative concept for process water extraction by capillary effect. In 1999, IFC disclosed a partnership with BMW for the delivery of 7 kW PEMFC systems to serve as APU (auxiliary power unit) in top class hydrogen BMW sedans, delivering electricity for zero emission onboard use for air conditioning and telecommunication.
Plug Power/ GE Fuel Cell Systems

Plug Power is a joint venture between DTE Energy Company and Mechanical Technology, Inc.. Plug Power together General Electric Power Systems has formed another joint venture, named GE Fuel Cell Systems, for the marketing of Plug Power manufactured PEMFC systems. The present state of development comprises a ≥4 kW, PEMFC system with Johnson Matthey fuel processor (HotSpot™). This natural gas system utilizes the same design as Plug Power’s 7 kW fuel cell prototype which has operated since June of 1998 on hydrogen and was the first PEM fuel cell system to provide a home’s complete electricity independent from the utility grid [see figure 6].

GE Fuel Cell Systems expects to begin selling residential-sized systems in 2001, and small business-sized (up to 35 kW) units by 2002. Retail prices for the residential system will be US$7,500 - 10,000 in 2001, and are expected to fall to less than US$4,000 by 2003 (probably US$ 3,500, i.e. < US$ 900/ kW_e-system).

Plug Power’s wants to become the first company to make and profitably sell one million fuel cell systems.

Plug Power was founded in June 1997 and since then has grown from 22 to more than 150 employees, actually being the largest PEM fuel cell company in the U.S.

Proton Motor GmbH

Founded by Magnet Motor of Starnberg, Germany, in 1998, the company holds several patents for innovative membran/ electrode assemblies which allow significant cost reduction and drastically reduced moisturization. The stack is supposed to be integrated to a rather simple and cost effective PEMFC system.

Since 1995, PEMFC stacks for atmospheric pressure are being developed for mass production (cost target < 200 DM/kW_e-stack. Without cooling system the specific parameters are 3.5 kg/kW_e and 3 l/kW_e. A 6 kW_e stack has been manufactured and tested [see figure 7], 30-50 kW_e stacks for automotive applications are presently under realization.

Proton Motor plans the realization of prototype vehicles by 1999.

Northwest Power Systems (NPS)

A 5 kW_e PEMFC system (stack delivered by DeNora, Italy) with methanol reformer (patented multi fuel steam reformer for methanol, ethanol or propane) has been presented in 1998 [see figure 6]. The hourly consumption of methanol lies in the order of 4 l. Electricity generation costs are expected to lie in the order of 14 cents_US/ kWh. The strategic partner for the testing phase is the Bonneville Power Administration (BPA). NPS has a proprietary multi-fuel steam reformer providing hydrogen at purity of 99.8% and a proprietary metal-membrane purifying hydrogen further to the purity levels required for PEMFC use.

The fuel cell system was used to power successfully a three-bedroom, 200 m² Bend, Oregon, residence. The home was disconnected from the electric power grid of Pacific Power & Light prior to the successful test and then reconnected afterwards. In a demonstration to experts and interested parties a variety of electrical loads typical of those found in a single-family home were demonstrated.

BPA will deliver the first 3 kW_e PEM fuel cell systems fall of 1999. Northwest utilities will test the units for use in homes. After the first ten ‘alpha’ units (85% total efficiency) are installed and operated, NPS will make any necessary adjustments and build 100 more ‘beta’ test units. The cost of producing the beta units is about $30,000 each. The price is expected to drop to under $10,000 per unit when they become commercially available in the year 2002. NPS aims to develop automated electric power generating systems ranging from 1 kilowatt to 10 kilowatts in power output by next year. BPA announced end of May of 1999 that it has signed a contract to purchase 110 fuel cells from NPS.
Siemens AG

Siemens AG of Erlangen, Germany, started its PEMFC development activities based on a licence obtained from General Electric in 1982. This licence agreement expired end of 1994. Since 1995, Siemens delivers PEMFC prototype units for hydrogen/oxygen operation to the German Navy for the propulsion of submarines. These systems composed of 72 cells with an active electrode area of 1180 cm² provide a continuous electric power output of 35 kWₑ and a short term peak electric power output of 55 kWₑ. Commercial delivery of series units to the German Navy has commenced in 1997.

Based on this technology a PEMFC system with a gross power output of 18 kWₑ operated with oxygen from air has been developed for a fork lift demonstration application at SWB (Solar Hydrogen Bavaria project). Presently, the development of 36 kWₑ units (30 kWₑ net power output) of this type is ongoing. Four of these units have been manufactured and tested and are presently integrated to a 120 kWₑ propulsion unit. This unit will be delivered to MAN for a low floor city bus with a short term maximum power rating of 150 kWₑ to be completely integrated by October 1999 and demonstrated in 2000.

In parallel, Siemens AG investigates and develops low cost mass producible PEMFC concepts which shall provide the basis for future low cost mass production of small stationary PEMFC units for various decentralized applications. Unfortunately Siemens has not yet taken the strategic decision to enter into mass production for commercial markets.

VAILLANT

The 125 year old manufacturer of gas heating systems plans to enter into the mass manufacturing and marketing of PEMFC cogeneration systems by 2005. A 5 kWₑ/7 kWₑ system shall undergo fleet testing with 50/400 units by 2001/2002 and mass delivery to the market with 10,000 units per year shall start by 2005 at installed unit costs of US$ 5,000.

OTHER organizations, companies or institutes active in the development of PEMFC membrane-electrode-membrane units, electrocatalysts, gas-diffusion electrodes, single cells, stacks, systems, portable power units and of methanol reformers are:

• BCS Technologies, Bryan, Texas, USA
• Consiglio Nationale Delle Ricerche CNR, S. Lucia, Messina, Italy
• DCH Technology, Inc., Valencia, CA, USA
• ElectroChem, Inc., Woburn, MA, USA
• Fraunhofer Institute for Solar Energy Systems, Freiburg, Germany
• Fuji Electric and Kansai Electric, Japan
• Hitachi, Japan
• Honda
• Humbold Sate University, Arcata, USA
• Los Alamos National Laboratories, USA
• Loughborough University, UK
• Lynntech, College Station, Texas, USA
• Mitsubishi Electric, Japan
• Netherlands Energy Research Foundation (ECN), Petten, The Netherlands
• NuPower (NUI Corporation and Energy Partners), USA
• Sanyo Electric, Japan
• Centre For Electrochemical and Energy Research SPIC Foundation, Madras, India
6.1.2 Demonstration Projects

**BEWAG**
The electric utility BEWAG of Berlin, Germany, together with its partners Hamburgische Electricitäts-Werke AG (HEW), Preussen Electra, Electricité de France (EdF) and VEAG plans to erect a Ballard PEM fuel cell cogeneration plant of a power output of 250 kW_e and 237 kW_th delivered by AEG of GEC Alstom. The plant will be fueled with natural gas which is converted to hydrogen by a natural gas reformer and purification equipment. The electric efficiency will be approx. 40%, the total efficiency (electric and thermal) will lie in the order of 80%. The size of the unit is 2.4 m x 2.4 m x 5.6 m (width/height/length) and the total weight reaches 12.5 t. The start-up time of the reformer is shorter than 2 hours. The plant shall be installed and started-up by October 1999.

**MUNICIPAL UTILITY OF MUNICH (SWM)/ MUNICH ENERGY AGENCY (MEA)**
Between 1990 and 1994, L B S T together with the municipal utility of Munich (SWM) investigated the feasibility of the admixture of hydrogen to municipal natural gas pipeline systems in selected blocks of the energy supply infrastructure of the city of Munich.

As a first step, a fuel cell partner still to be selected will be deliver to MEA and test a 2-5 kW_e PEM fuel cell cogeneration system by the end of 1999/ beginning of 2000.

**ELECTRO-FARMING PROJECTS IN BAVARIA**
In two Bavarian communities biomass gasification pilot plant projects are under investigation. Via pressurized water vapor gasification of biomass a hydrogen rich synthesis gas shall be produced, purified to 99.99% of hydrogen and fed to its largest share into PEMFC cogenerator (combined power and heat production) and to its minor share provided as vehicle fuel. Another concept foresees the use of an MCFC which does not require the hydrogen purification step but can cope with synthesis gas produced by the biomass gasifier directly. If one of the concepts can be proven as feasible and economically competitive it shall be commercialized and installed in several Bavarian communities for the treatment of waste biomass for the provision of clean locally produced energy and possibly for the delivery of vehicle fuels (in case the PEMFC concept is selected).

6.2 Mobile applications

6.2.1 City and transit buses:

**Ballard Power Systems**
Low floor transit bus based on New-Flyer model 40 LF with 12.2 m length
PEM-fuel cell drive by Ballard with a net power output of 205 kW_e
compressed gaseous hydrogen (CGH2) storage at 25 MPa pressure in carbon fiber composite materials tanks
Operating range of 400 km to 560 km (with break energy recovery)
Passenger capacity of approx. 75 persons
Maximum speed, depending on drive axle gear ratio, approx. 95 km/h
Fleet tests in small-scale fleets of 3 buses each in Chicago and Vancouver [see figure 9] since 1998
Public price of the present prototype version in 1997 is 1.4 million US$ per bus unit
Price goal for small-scale series in 2001 lies in the order of US$ 600,000 per bus unit (double the price of a compressed natural gas bus or equal to a north-American trolleybus; in 2004 sales prices in the order of those for natural gas buses are scheduled, i.e. US 300,000)

**DaimlerChrysler – NEBUS** [see figure 11]
Low floor city bus with a length of 12 m
PEM-fuel cell drive with 10 Ballard/ DaimlerChrysler stacks of 25 kW each gross power output providing 190 kW net power output
Compressed gaseous hydrogen (CGH₂) storage at 30 MPa level in 7 aramid fiber tanks of 147 l geometric volume each containing in total some 45,000 l of hydrogen providing 250 km operating range
Passenger capacity of 58 persons (34 seated, 24 standing)
Wheel hub motor by ZF
Maximum speed, depending on drive axle gear ratio, approx. 85 km/h
Presented on May 26, 1997 in Stuttgart/ Demonstration operation at UIPT conference/ Two week demonstration in Mexico City in December 1998/ Further demonstration and number of demonstrators still to be decided

**Georgetown University/ H Power**
Mid-transit bus with a length of 9 m
Hybrid propulsion concept with NiCd-battery storage for peak demand and hill climbing
PAFC Fuel Cell stack by Fuji Electric (former Englehard) with 55 kW
Methanol reformer for onboard hydrogen production from liquid methanol/water mixtures
Operating range approx. 300 km
Pilot testing of the three prototypes at several locations in the USA since 1993

**H Power Corp.**
Transit bus with a length of 12 m
Hybrid propulsion concept including battery storage
PEM-fuel cell propulsion by H Power (integrated fluid management PEMFC technology) with approx. 50-70 kW PEMFC power
JP8 fuel operation via underoxidized burner (from HBT) for onboard hydrogen generation
Operating range > 300 km
Partners: ANL, DoE, Georgetown University, H Power
Sponsors: DoE, SCAQMD, DoT
Demonstration in Sacramento by SMUD end of 1999

**MAN NL 163 BZ** [see figure 10]
Low floor city bus with a length of 12 m
PEM-fuel cell drive of approx. 120 kW net by Siemens composed of four fuel cell modules of 30 kW each
Compressed gaseous hydrogen (CGH₂) storage at 25 MPa level in 9 carbon fiber reinforced composite materials tanks of 170 l each providing a total geometric volume of 1530 l
Operating range of 200-300 km at a consumption of 8 kg-H₂/h at rated power output
Passenger capacity of 60 persons
Maximum speed, depending on drive axle gear ratio, approx. 75 km/h
6 month demonstration operation in Bavaria (presumably Erlangen) in the year 2000
Project partners: Linde GA, LBST, MAN Nutzfahrzeuge AG, MAN Technologie AG, Siemens KWU and Siemens VT

MAN NL 223 BZ
Low floor city bus with a length of 12 m and 18 t
PEM-fuel cell drive of approx. 120 kW$_{net}$ by Air Liquide/ DeNora composed of four fuel cell modules of 30 kW$_e$ each
Liquid hydrogen (LH$_2$) storage in 2 LH$_2$ storages of 350 l each
Operating range of approx. 300 km
Passenger capacity of 60 persons
Maximum speed, depending on drive axle gear ratio, approx. 75 km/h
Demonstration operation in Berlin (9 months), Lisbon (2 months) and Copenhagen (1 month)
Project partners: MAN Nutzfahrzeuge AG [D], Air Liquide [F]/ Air Liquido [P], BVG Berlin [D], Carris [P], HAT [DK], IST [P], Senate of Berlin/ InnoTec [D] – Funding by European Commission’s DG XVII, Thermie A

Neoplan
Low floor midi-bus based on composite materials bus type N 8008 with a length of 8 m
Parallel hybrid propulsion concept using a fuel cell and a NiMH battery storage system
PEM-fuel cell system with 50 kW$_e$ by De Nora
Compressed gaseous hydrogen (CGH$_2$) storage
Passenger capacity of 40 persons
Maximum speed 30 to 50 km/h
System integration with assistance of DLR, Stuttgart
Demonstration presumably in the Bavarian community of Oberstdorf in 1999

6.2.2 Passenger cars, vans and utility vehicles with fuel cell propulsion:

Coval H2 Partners
Small distribution truck (2.3 t total weight) with battery propulsion; 6 V lead acid battery; 85 hp electric drive motor
6.5 kW$_e$ PEMFC [0.3 m x 0.2 m x 0.6 m] by DeNora, operated at 0.2 MPa air pressure serves as range-extender
Operating range with battery: 65 km; with two compressed gas storage vessels (1 kg H2): 130 km

Ford Fuel Cell Passenger Car Prototypes
Advanced lightweight vehicle concept with approx. 900 kg weight (Partner: Alcan Aluminum)
Compressed hydrogen storage at 34.5 MPa pressure level in carbon composite materials tanks of liquid hydrogen storage assuring hydrogen storage of 3.58 kg.
Operating range at a fuel economy of 2.9 l/100 km (80 mpg) as required by the PNGV program approx. 600 km (380 mi); at least 465 km (290 mi); probably if drag coefficient can be reduced to 0.2, then even 700 km (440 mi) may be achieved.
One of the three prototype vehicles planned will be equipped with an LH$_2$ storage supplied by Messer.
[Since end of 1997 Ford Motor Co., Dearborn, USA, is development partner of DaimlerChrysler AG, Stuttgart/ Auburn Hills, in the commercialization phase of PEMFC drives for passenger cars together with Ballard Power Systems Inc., Burnaby, British Columbia, Canada]
DaimlerChrysler Necar II

Mini-Van with an operating range of approx. 2.5 t (Length 4659 mm, width 1870, height 2380 mm)
PEM-fuel cell drive system composed of 2 high performance stacks with in total 50 kW\textsubscript{e} gross power output at an air pressure of approx. 0.3 MPa and a specific system weight of 6 kg/kW\textsubscript{e} (at a voltage of 180-280 V)
Electric three phase A.C. motor of 33 kW\textsubscript{e} via two stage automatic transmission
Compressed gaseous hydrogen (CGH\textsubscript{2}) storage at 25 MPa level in 2 carbon fiber composite materials tanks of 140 l geom. volume each (Length 1895 mm, diameter 351 mm)
Operating range > 250 km
Passenger capacity of 6-7 persons
Maximum speed of 110 km/h
Prototype was presented in May of 1996

DaimlerChrysler A-Model \[NECAR III, NECAR IV and NECAR V\] \[see figure 11\]

Micro compact car
PEM-fuel cell drive system with 2 high performance stacks of in total 50 kW\textsubscript{e} gross power output at an air pressure of approx. 0.3 MPa and a specific system weight of 6 kg/kW\textsubscript{e} (at a voltage of 180-280 V)
Operating range of up to 450 km
Hydrogen onboard storage in form of liquid methanol and compact methanol reformer for onboard hydrogen production \[NECAR III and V\]
Respectively onboard storage in form of liquid hydrogen \[NECAR IV\]
Passenger capacity of 4-5 persons
Maximum speed of > 110 km/h, 145 km/h for NECAR IV
Prototype presentation of NECAR III in fall of 1997, of NECAR IV in March of 1999 and of NECAR V early in 2000
Fuel consumption for NECAR IV in driving cycle approx. 1.1 kg-H\textsubscript{2}/100 km (or 3.7 l\textsubscript{DE}3/100 km)
Series production in second generation A-model possible around 2005 if cost goals can be achieved.
Mass production volumes of 40,000, 70,000 and 100,000 units per year shall be achieved by 2004, 2005 and 2006 respectively according to DaimlerChrysler target planning.

Energy Partners, Inc., "Gator"

Utility vehicle prototype (weight: 600 kg, payload: 544 kg) based on John Deere chassis
PEM-fuel cell drive system of 10 kW\textsubscript{e} gross power output
Membrane-electrode-assembly by W.L. Gore (PRIMEA\textsuperscript{TM})
Electric drive motor of 8 kW\textsubscript{e} at 48 VDC
Compressed hydrogen storage of 22.7 Nm\textsuperscript{3} at 20 MPa
Operating range approx. 125 km, refueling time 5 minutes
Passenger capacity of 2 persons
Maximum speed of approx. 24 km/h
Prototype was presented in 1996

Energy Partners, Inc., "Genesis"

Passenger transport vehicle prototype (weight: 680 kg, payload: 1133 kg) based on golf cart chassis by E-Z-Go
PEM-fuel cell drive system of 7.5 kW\textsubscript{e} gross power output
Electric direct drive motor of 7 kW\textsubscript{e} at 48 VDC
Compressed hydrogen storage of 7 Nm\textsuperscript{3} at 20 MPa and compressed oxygen storage at 20 MPA
Operating range approx. 72 km, refueling time 15 minutes
Passenger capacity of 8 persons
Maximum speed of approx. 24 km/h
Prototype was presented in 1995
Genesis II and Genesis III with 20 kWₑ respectively 50 kWₑ are planned for the future

**Energy Partners, Inc., "Green Car"**
Sports car prototype (weight: 1360 kg) based on chassis by Consulier
PEM-fuel cell/battery hybrid drive system with a PEMFC gross power output of 15 kWₑ from three fuel cell stacks
Brushless electric drive motor of 25.5 kWₑ
Compressed hydrogen storage of 11.7 Nm³ at 20 MPa
Operating range approx. 96 km, refueling time 15 minutes
Passenger capacity of 2 persons
Maximum speed of approx. 96 km/h
Prototype was presented in 1993

**Global Fuel Cell Corporation (GFC)**
GFC plans to integrate its PEMFC technology into an electric mini-van with a state of the art AC drive system.
A series of vehicle runs are planned over the next few months with the fuel cell using a variety of fuels including hydrogen, natural gas, propane, methanol & gasoline.

**GM/ Opel Zafira [see figure 12]**
Minivan for originally 7 passengers – the driveable fuel cell demonstrator provides only two utilizable seats
2 PEM fuel cell stacks of 25 kWₑ each by Ballard
Methanol onboard reformer with catalytic heater; Methanol storage tank of 54 l; Water storage tank of 20 l
Buffer batteries of advanced Ovonic NiMH pack (315 HEV20) type
50kW AC induction motor with fixed gear ration actuating on front wheel
Maximum velocity: 120 km/h; Acceleration 0 ... 100 km/h: 20 s
Total weight: 1850 kg
Vehicle presented at Paris Motor Show, Sept.. 1998
[GM PEMFC stack also presented in Paris, but not integrated in vehicle, consisted of 180 cells providing 125 V or 34 kWₑ at 48 kg of weight with outer dimensions of 0.4 m x 0.4 m x 0.25 m]

**Honda**
Honda is working with three companies to develop a proprietary fuel cell technology that will be lighter and more compact than those currently offered by Ballard Power Systems
Honda works on a PEMFC vehicle to based on the EV Plus compact electric sedan which shall be built in 300 units per year starting in 2003 for sale in Japan and the U.S.. Honda Motor Co. intends to spend between 50 billion yen and 60 billion yen ($419 million and $500 million) to introduce the fuel-cell powered vehicle by 2003.
Onboard storage of fuel is intended to be realized with methanol. If this should not be feasible (e.g. due to corrosion) or if gas stations aren't allowed to store methanol, Honda will be able to switch to pure hydrogen.

**International Fuel Cells (IFC)**
During the last 10 years, IFC has developed a PEMFC system which provides 50 kWe power output.
The system, presented in fall 1997, operates at ambient pressure and thus does not need an air compressor.
The system operates with pure hydrogen, weighs approx. 135 kg and has a volume of 240 l.
In the next years, IFC plans to develop a 50 kWe system for passenger car application which shall posses a multi-fuel reformer.

**Mazda Demio Fuel Cell Midi-Van [12/1997]**
Prototype vehicle (not foreseen for commercialization)
- 20 kWe PEMFC
- Supercapacitor as buffer storage for demand peaks and break energy recovery
- Electric motor with 40 kWe power output
- Metal hydride storage for 15 Nm3 sufficient for an operating range of approx. 170 km
- Maximum speed approx. 90 km/h

**Mitsubishi**
Mitsubishi Motors Corp. and Mitsubishi Heavy Industries Ltd. together develop PEMFC vehicles and plan to present a series producible vehicle in 2005.

**Nissan**
Nissan works on a PEMFC hybrid-electric vehicle with methanol onboard reforming and lithium-ion battery.
A series producible vehicle is to be expected between 2003 and 2005

**Proton Motor GmbH**
Proton Motor plans the realization of prototype vehicles to be equipped with its low cost ambient pressure PEMFC system by 1999, among them a passenger car with 50 kW and a bus with 70 kW PEMFC systems to be combined with battery systems to hybrid propulsion systems.

**Plug Power, Automotive**
In October 1997. PlugPower togehter with the US DoE, Arthur D. Little and Alamos Natl. Laboratory presented the first gasoline fueled PEMFC system (approx. 1 kWe) which generates hydrogen through a POX (partial oxidator) from gasoline.
In May 1999 PlugPower presented a PEMFC system with Epyx multi-fuel processor which claims to achieve an overall tank-to-wheel efficiency of 40%.

**PSA Peugeot Van**
Peugeot Berlingo van of approx. 2 t operating weight
- PEM-fuel cell drive system with 2 or 3 De Nora stacks with in total 30 kWe gross power output at an air pressure of 0.12-0.14 MPa
- Small battery for peak demand coverage
- Fuel cell propulsion system by De Nora
- Ultra high compressed gaseous hydrogen storage at 70 MPa in some 4 composite materials tanks with a metallic inner liner by CEA, France, providing a hydrogen storage capacity of 5 kg for an operating range of approx. 300 km
- Passenger capacity of 5 persons
- Maximum speed of > 100 km/h
- Presentation of prototype by 1999
Renault Laguna Break

Medium sized station wagon
PEM-fuel cell drive system with 3 De Nora stacks of in total 30 kWel gross power output at an air pressure of 0.35 MPa
Battery for coverage of acceleration peak and hill climbing demand; Electric propulsion system by Ansaldo Ricerche
LH₂ storage by Air Liquide for an operating range of 500 km at a speed of 100 km/h
Passenger capacity 2 + persons
Maximum speed of 120 km/h
Presentation of prototype in summer of 1997, Series production possible by 2010

Toyota RAV4L V

Fun Vehicle (Length 3975, width 1695 m, height 1635 mm)
PEM-fuel cell drive system of 20 kWel gross power output, 120 kg weight and 60% stack efficiency
Front wheel drive via synchronous permanent magnet electric motor of 45 kWel and max. torque of 165 Nm
Hydrogen storage for 2 kg of hydrogen in a metal hydride storage of 100 kg weight
Operating range approx. 250 km
Passenger capacity of 5 persons
Maximum speed of approx. 100 km/h
Prototype was presented by fall of 1996, improved prototypes will be presented every coming year

Toyota RAV4L V [1997]

Fun Vehicle (Length 3975 mm, width 1695 mm, height 1635 mm)
Proprietary PEMFC System (1,08m x 0,5 m x 0,24 m) of 25 kWel gross power output, 120 kg weight and 60% stack efficiency
Ni-MH-battery system (288 V) for break energy recovery and peak demand coverage
Front wheel drive via synchronous permanent magnet electric motor of 50 kWe and max. torque of 190 Nm
Fuel storage in a methanol tank
Methanol evaporation, -reforming, CO oxidation and gas purification in a 0,6 m long and 0,3 m thick onboard integrated unit
Operating range: ca. 250 km
Seating capacity: 5 persons
Maximum velocity: approx. 125 km/h
This prototype was presented at the IAA Frankfurt and the Toyko Motor Show in fall of 1997

Volkswagen

Until the year 2000, VW plans to realize a Golf station wagon with PEMFC drive system and onboard autothermal methanol reforming

ZEVCO Ltd.

Prototype of a British cab with hybrid-electric drive consisting of a NiMH-battery of 220 Ah at 300 V and an alkaline fuel cell system (AFC) of presently in total 5 kWel (soon 10 kWel) providing a total propulsion power output of 45 kWel.
Presently hydrogen is stored in pressure vessels. In the future H₂ shall be stored in activated carbon storage to be delivered by SEP, France.
ZEVCO furthermore intends to realize AFC propulsion units for luggage trolleys (TUG Corp.), fork lifts (Still), 12 m city buses (Robert Wright and Company), midi-buse (Pontichelli), light rail systems (Parry People Movers Ltd.), mail delivery vehicles (Pasquali) and municipal micro delivery vans (Subaru Cityvan).

Netram [still in negotiation]:
Prototype tramway with PEMFC-electric drive system and CGH2 onboard storage
Parallel to the hydrogen buses of the planned Karlsruhe bus demonstration project also this PEMFC tramway shall be refueled at the CGH2 refueling station
Project duration: 1999 – 2003 (including a 2 years demonstration phase)
Project Management and Monitoring: IABG, LBST

7. COMMERCIALIZATION INITIATIVES AND SCHEDULES
7.1 Stationary applications

<table>
<thead>
<tr>
<th>Fuel Cell Company</th>
<th>Type of FC System</th>
<th>Target Year of Market Entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>American Power</td>
<td>3.5 kW_e / 4.5 kW_h</td>
<td>2003</td>
</tr>
<tr>
<td>Avista Labs</td>
<td>0.72 kW_e subrack</td>
<td>Prototype by 1999</td>
</tr>
<tr>
<td>Ballard Power Generation Systems</td>
<td>1 kW_e and 250 kW_e / 237 kW_h</td>
<td>1999 and 2001</td>
</tr>
<tr>
<td>DeNora</td>
<td>15-20 kW_e and 50 kW_e</td>
<td>After 2000</td>
</tr>
<tr>
<td>Energy Partners</td>
<td>1-10 kW_e</td>
<td>2001</td>
</tr>
<tr>
<td>H Power</td>
<td>2.5/10 kW_e</td>
<td>10 prototypes by 1999 Commercial after 2000</td>
</tr>
<tr>
<td>Northwest Power Systems</td>
<td>3 kW_e</td>
<td>2002</td>
</tr>
<tr>
<td>Plug Power/GE Fuel Cell Systems</td>
<td>4 kW_e and 35 kW_e</td>
<td>2001</td>
</tr>
<tr>
<td>Proton Motor GmbH</td>
<td>X kW_e</td>
<td>After 2000</td>
</tr>
<tr>
<td>Vaillant</td>
<td>5 kW_e / 7 kW_h</td>
<td>2005</td>
</tr>
<tr>
<td>Siemens</td>
<td>5 kW_e / 9 kW_h</td>
<td>Prototype 1999</td>
</tr>
</tbody>
</table>
7.2 Mobile applications

<table>
<thead>
<tr>
<th>Fuel Cell / Automotive Company</th>
<th>Type of FC System</th>
<th>Target Year of Market Entry</th>
</tr>
</thead>
<tbody>
<tr>
<td>DaimlerChrysler/ Ballard/ Ford</td>
<td>50/70 kW \text{e}</td>
<td>2004: 40,000 units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2005: 70,000 units</td>
</tr>
<tr>
<td></td>
<td></td>
<td>≥ 2006: 100,000 units/yr</td>
</tr>
<tr>
<td>Energy Partners/ John Deere</td>
<td>&gt; 10 kW \text{e}</td>
<td>After 2000</td>
</tr>
<tr>
<td>General Motors/ Opel</td>
<td>2 x 25 kW \text{e} by GM</td>
<td>Prototype by 1998</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&gt; 2010: 10% of all sales</td>
</tr>
<tr>
<td>Global Fuel Cell Corporation</td>
<td>Proprietary low cost PEMFC</td>
<td>Mass production after 2000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Large volumes by 2003</td>
</tr>
<tr>
<td>Honda Motor Corp.</td>
<td>Proprietary PEMFC technology</td>
<td>2003</td>
</tr>
<tr>
<td>H Power</td>
<td>2.5-50 kW \text{e}</td>
<td>Prototype by 1999</td>
</tr>
<tr>
<td>International Fuel Cells</td>
<td>7 kW \text{e} for onboard APU (BMW)</td>
<td>1999</td>
</tr>
<tr>
<td></td>
<td>50 kW \text{e} + POX for propulsion</td>
<td>after 2000</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>OEM</td>
<td>2005</td>
</tr>
<tr>
<td>Nissan Motor Corp.</td>
<td>OEM</td>
<td>2003</td>
</tr>
<tr>
<td>Plug Power</td>
<td>PEMFC + POX</td>
<td>After 2000</td>
</tr>
<tr>
<td>PSA</td>
<td>With DeNora PEMFC (OEM)</td>
<td>Prototype 1999</td>
</tr>
<tr>
<td>Proton Motor GmbH</td>
<td>30-70 kW \text{e}</td>
<td>Prototype 1999</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Commercial after 2002</td>
</tr>
<tr>
<td>Siemens AG</td>
<td>35 kW \text{e} module</td>
<td>Prototype 1999</td>
</tr>
<tr>
<td>Toyota Motor Corp.</td>
<td>Proprietary PEMFC technology</td>
<td>Approx. 2005</td>
</tr>
<tr>
<td>Volkswagen Motor Corp.</td>
<td>OEM</td>
<td>Prototype by 2000</td>
</tr>
</tbody>
</table>

8. FUEL SUPPLY PATHS AND REFUELING CONCEPTS FOR FUEL CELL APPLICATIONS

8.1 Fuel supply paths [see figure 13]

Basically three fuel supply and onboard storage approaches for fuel cell vehicles can be differentiated:

1. hydrogen storage in compressed gaseous (high pressure tanks, metal hydrides, graphite nanostructures) or liquid form (cryogenic liquid, cryo-adsorption) [potentially from renewable sources - potentially without any emissions]

2. hydrogen storage in hydrogen rich liquid methanol [potentially from renewable sources - potentially with very low emissions]

3. hydrogen storage in hydrogen rich hydrocarbons such as gasoline- or diesel-type fuels [from fossil sources - with emissions rather high emissions, or synthesized from renewable energy sources with still moderate emissions]

Concept 3 does not require any infrastructural changes for its supply and thus would be the ideal starter scenario. On the other hand it prevents the introduction of renewable energy sources into the transport sector as true zero emission alternative.

Concept 2 requires only moderate infrastructural changes (exchange of some gasket and hose materials, corrosion resistive tank and tube materials, spill collection, vapor collection). This concept would also allow the introduction of renewable energy from biomass or via hydrogenation of CO\textsubscript{2}.

Concept 1 requires major infrastructural changes but provides the possibility for a very flexible introduction of renewable energy sources into the transport sector. Since the infrastructure adaptation will require several years, concept 1 is only suitable as long term scenario at large scale or as niche starter scenario within a few years.

An overview on existing or presently developed hydrogen storage technologies is given in table 8.1 below.
Table 8.1: Hydrogen Storage Concepts

<table>
<thead>
<tr>
<th>STORAGE SYSTEMS</th>
<th>VOLUMETRIC STORAGE CAPACITY [g H₂ / l]</th>
<th>MASS SPECIFIC STORAGE CAPACITY [g H₂ / kg]</th>
<th>VOLUMETRIC ENERGY CONTENT [kWh / l]</th>
<th>MASS SPECIFIC ENERGY CONTENT [kWh / kg]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed gas vessel 25 MPa (Full composite mat.)</td>
<td>17,5</td>
<td>64</td>
<td>0,6</td>
<td>2,15</td>
</tr>
<tr>
<td>Liquid hydrogen (-253°C/ 20 K)</td>
<td>35</td>
<td>105</td>
<td>1,2</td>
<td>3,5</td>
</tr>
<tr>
<td>Metal hydride - today (room temperature)</td>
<td>80</td>
<td>10</td>
<td>2,7</td>
<td>0,35</td>
</tr>
<tr>
<td>Metal hydride – future (room temperature)</td>
<td>&gt; 160</td>
<td>20 - 25</td>
<td>&gt; 5</td>
<td>&gt; 0,7</td>
</tr>
<tr>
<td>Methanol</td>
<td>ca. 95</td>
<td>ca. 120</td>
<td>4</td>
<td>3</td>
</tr>
<tr>
<td>Sponge iron</td>
<td>ca. 65</td>
<td>ca. 35</td>
<td>1,4</td>
<td>0,7</td>
</tr>
<tr>
<td>Carbon Nano Tubes – K doped</td>
<td>126</td>
<td>140</td>
<td>4,2</td>
<td>4,66</td>
</tr>
<tr>
<td>Carbon Nano Tubes – Li doped</td>
<td>180</td>
<td>200</td>
<td>6,0</td>
<td>6,66</td>
</tr>
<tr>
<td>[laboratory values/ without tank]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Graphite nanofiber (Laboratory)</td>
<td>~ 450</td>
<td>~ 430</td>
<td>~ 15</td>
<td>~ 14</td>
</tr>
</tbody>
</table>

Table 8.2: Comparison of Fossil Derive Fuel Supplied Propulsion Concepts

<table>
<thead>
<tr>
<th></th>
<th>Gasoline + ICE</th>
<th>Compressed Hydrogen from Natural Gas</th>
<th>Methanol from Natural Gas</th>
<th>Gasoline + POX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Supply Efficiency [%]</td>
<td>90</td>
<td>63-72</td>
<td>67-71</td>
<td>90</td>
</tr>
<tr>
<td>Onboard Fuel Efficiency [%]</td>
<td>19-20</td>
<td>35-43</td>
<td>25-34</td>
<td>21-30</td>
</tr>
</tbody>
</table>

Assumption: MVEG Driving Cycle, Passenger Car of 1,000 kg, Fuel Consumption 5 l/100 km for ICE, Hydrogen and Methanol Source is Natural Gas

Source: [20]
Table 8.3: Comparison of Fossil Derive Fuel Supplied Propulsion Concepts

<table>
<thead>
<tr>
<th>Type of Propulsion</th>
<th>Type of Fuel</th>
<th>Relative On-Board Fuel Efficiency [%]</th>
<th>Fuel Supply Efficiency [%]</th>
<th>Total Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ICE</td>
<td>Gasoline</td>
<td>100</td>
<td>90</td>
<td>90</td>
</tr>
<tr>
<td>PEMFC</td>
<td>CGH₂ from NG</td>
<td>275</td>
<td>64</td>
<td>176</td>
</tr>
<tr>
<td>PEMFC + Reformer</td>
<td>MeOH (high)</td>
<td>196</td>
<td>62</td>
<td>122</td>
</tr>
<tr>
<td></td>
<td>MeOH (low)</td>
<td>169</td>
<td>62</td>
<td>105</td>
</tr>
<tr>
<td></td>
<td>From NG</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEMFC + POX</td>
<td>Gasoline (high)</td>
<td>170</td>
<td>90</td>
<td>153</td>
</tr>
<tr>
<td></td>
<td>Gasoline (low)</td>
<td>119</td>
<td>90</td>
<td>107</td>
</tr>
</tbody>
</table>

Sources: [18], [19]

Tables 8.2 and 8.3 display two sets of comparison of fuel supply paths together with propulsion concepts. In both cases conventional crude oil derived gasoline consumed in conventional internal combustion engines and in PEM fuel cell drives with onboard partial oxidation (POX) are compared with methanol + onboard reforming and hydrogen stored onboard in compressed form, both derived from natural gas.

The efficiency values given for the two independently elaborated comparisons show very impressively that the hydrogen onboard storage path is the energetically most efficient one (although the assumptions were selected rather conservatively). These findings are proved by own LBST simulations and calculations, among others performed for city buses [see figure 14].

On the other hand, the gasoline path is on the more optimistic side, since the fuel supply paths were assumed very much on the optimistic side, as the assumed onboard POX-conversion efficiencies can only be achieved with completely clean synthetic hydrocarbons derived from natural gas which then would not reach the supply efficiencies of today's conventional hydrocarbon supply paths.

The methanol supply efficiencies in table 8.3 are most likely too pessimistic and most probable the efficiencies assumed in the upper range of table 8.2 will be achieved at mid-term.

Thus only hydrogen and methanol seem to provide the potential for efficient fuel supply also from renewable energy sources. For both fuels infrastructural difficulties have to be solved, which for methanol usually are underestimated and for hydrogen overestimated. Hydrogen furthermore deals with an image problem in the public which is related to some spectacular accidents in the past of which none originated from hydrogen itself but were hydrogen only in a secondary step was ignited (e.g. burning of the Hindenburg Zeppelin, burning and explosion of the Challenger space shuttle). As the major technical problem related to hydrogen can be regarded the onboard storage. Also in this respect improved concepts are under development (e.g. graphite nano-tube and nano-fiber storage, improved pressurized cryogenic liquid hydrogen storage, high pressure composite materials storage).
Table 8.4: Comparison of Different Fuel Supply Paths for Fuel Cell Vehicles

<table>
<thead>
<tr>
<th>Generation Site</th>
<th>Vectorization Path</th>
<th>Well – to - Fuel Station Efficiency</th>
<th>Well – to - Wheel Efficiency for PEMFCV</th>
</tr>
</thead>
<tbody>
<tr>
<td>German Windpower</td>
<td>CGH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.60</td>
<td>0.24</td>
</tr>
<tr>
<td>Patagonian Windpower</td>
<td>LH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.37</td>
<td>0.15</td>
</tr>
<tr>
<td>Canadian Hydropower</td>
<td>LH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.45</td>
<td>0.18</td>
</tr>
<tr>
<td>Solar Thermal Energy North Africa</td>
<td>LH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.43</td>
<td>0.17</td>
</tr>
<tr>
<td>Natural Gas Germany</td>
<td>CGH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.55</td>
<td>0.22</td>
</tr>
<tr>
<td>Electric Grid Germany</td>
<td>CGH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.22</td>
<td>0.09</td>
</tr>
<tr>
<td>Biomass Germany</td>
<td>CGH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.47</td>
<td>0.19</td>
</tr>
<tr>
<td>Natural Gas + Off-Shore Windpower</td>
<td>LH&lt;sub&gt;2&lt;/sub&gt;</td>
<td>0.54</td>
<td>0.22</td>
</tr>
<tr>
<td>Natural Gas Germany</td>
<td>MeOH</td>
<td>0.65</td>
<td>0.22</td>
</tr>
<tr>
<td>Crude Oil North Sea</td>
<td>Gasoline</td>
<td>0.83</td>
<td>0.23</td>
</tr>
</tbody>
</table>

Explanation: CGH<sub>2</sub> = compressed gaseous hydrogen (35 MPa), LH<sub>2</sub> = cryogenic liquid hydrogen (at 20 K), MeOH = methanol

Well-to-Fuel Station Efficiency takes into account fuel production, conditioning and transport from well to pump with today best available industrial technology

Well-to-Wheel Efficiency combines Well-to-Fuel Station Efficiency with On-board Fuel Cell Efficiency [differentiated according to hydrogen, methanol or gasoline vehicle] over the same driving cycle in a standardized vehicle.

8.2 Refueling concepts for hydrogen:

Like for natural gas (CNG ‘compressed natural gas’ and LNG ‘liquid natural gas’) typically two ways of dispensing hydrogen fuel exist: compressed gaseous hydrogen (CGH<sub>2</sub>) and liquid cryogenic (LH<sub>2</sub>). Both technologies have been tested or are being tested only in prototype refueling applications in several countries (Belgium, Canada, France, Germany, Japan, USA).

For CGH<sub>2</sub> typically onboard storage pressure levels of between 20 MPa and 25 MPa have to be supplied by the refueling station. Usually air piston compressors are used to pressurize gaseous hydrogen from very low pressure levels (e.g. several mbar to several bars) to the pressure levels required for onboard storage (slow fill procedure, typically over night) or to the pressure level required in the stationary storage banks (typically with pressure levels of between 30 MPa and 40 MPa). With the higher pressure levels typical for storage banks fast fill procedures are possible, allowing the refueling of vehicles in a few minutes via the existing pressure differential (like today with larger CNG refueling stations). One existing type of reciprocating hydraulic piston compressor allows suction pressure levels of between 0.04 MPa and 20 MPa and pressurization to up to 40 MPa. Thus the storage volume of the storage banks can be used much more efficiently and the refueling process accelerated additionally.

For LH<sub>2</sub> refueling vacuum super-insulated equipment (storage vessels, hoses, pipes) is required in order to minimize the losses of cryogenic liquid product [-253°C or 20 K] due to evaporation into the gaseous phase (boil-off) caused by heat intrusion into the system. Based on the experience accumulated in several demonstration projects in Germany during the last two decades, the following measures for improvement have been identified and already partly been integrated in most recent technological concepts.

Although cryogenic systems impose stringent technological and thermal requirements their use can be of advantage for vehicles with high daily operating range needs (such as city buses) since they reduce storage
weight and volume compared with CGH₂. LH₂ refueling of a 125 l tank required about one hour and caused losses of up to 50% of the entire product volume by 1990. Systematic improvement of many process parameters and components (see above) executed in the framework of the Solar Hydrogen Bavaria Project in Germany led to refueling times of less than 3 minutes at 0 losses by end of 1996. These advances achieved by BMW and its partners Linde and Messer are used for the worldwide first public LH₂ robot refueling station at the Munich Airport opened end of April 1999. BMW there will start with one vehicle in 1999 and increase the number to at least five cars by the year 2000. A total of about 15 vehicles (including those 5 operated in Munich) will be demonstrated during EXPO 2000 in Germany in the year 2000.

The energy requirements for LH₂ production are still higher than for hydrogen compression but might be compensated in vehicle applications due to the lower storage weights (which have an influence on fuel consumption during acceleration phases). In today's liquefaction plants (5 – 30 t/d) the energy consumed for liquefaction is about 30% of the energy content contained in the LH₂ produced. In large liquefaction plants (300 t/d are presently analyzed) this energy requirement can fall to 20%. Compression of hydrogen to 25 MPa, depending on the quality of the compressor, requires energy inputs of in the order of 9-12% of the energy contained in the compressed hydrogen generated.

A combination of both concepts in a so called LCGH₂-refueling process offers the opportunity to compress LH₂ as liquid with a small cryogenic pump and with very little energy input. This compressed LH₂ than will be evaporated through a vaporizer into a pressure storage vessel and stored there as CGH₂. This concept allows the efficient delivery of LH₂ and its use as CGH₂ but is only sensible if LH₂ is produced cheaply and a logistics chain already is available.

Advantage of CGH₂ storage is its flexibility with respect to the hydrogen source. Hydrogen can be produced on the spot either from natural gas via steam methane reforming or partial oxidation, from biomass via gasification, or from electricity via electrolysis of water and then will be compressed with a compressor station, stored in a pressure bank system and then can be dispensed to the vehicle. LH₂ cannot yet be produced in a decentralized way on the spot (small-scale liquefaction technology is not available in sufficiently efficient units and will not be in the foreseeable future) but always has to be trucked in from a large liquefaction plant usually located far distant.
### Table 8.5: Hydrogen Refueling Concepts used in Demonstration Projects

<table>
<thead>
<tr>
<th>Project</th>
<th>CGH₂</th>
<th>LH₂</th>
<th>LCGH₂</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bavarian Bus Demonstration Project [04/96 – 08/98]</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Renault FEVER PEMFC Demonstration [1997]</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Clean Air Now – LA [since 1998]</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hamburg Van Demonstration Project (W.E.I.T.) [start: 12.01.99]</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chicago Transit Authority Ballard PEMFC Bus Demo [03/98-02/2000]</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Munich Airport Vehicle Project [05/99 – 2001]</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Belgian Bus Demonstration Project [start end of 1999]</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HydroGen PSA Van Demonstration [to start end of 99/ beginning of 2000]</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PEMFC Vehicle Demonstration by WE-NET [to start earliest by 2001]</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
9. **LITERATURE**


[3] Jörg Schindler and Werner Zittel, For how much longer will the cheap oil last?, L-B-Systemtechnik GmbH, January 1999


