HYDROGEN-FUELED BUSES:
THE BAVARIAN FUEL CELL BUS PROJECT

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1. PROJECT GOALS AND TECHNICAL OBJECTIVES

The goal of the project was to build and operate a prototype fuel-cell powered city bus in public revenue service. The bus was equipped with proton exchange membrane fuel cells (PEMFC) and an onboard compressed hydrogen storage system. The integration of a new power train and fuel storage and supply system should provide new experiences with respect to system integration and operation requirements. This project was designed to facilitate the technical and economic optimization of the entire bus concept, as well the development and optimization of single system components. By approving the hydrogen-fueled FC bus for public passenger transport, important safety issues will be addressed and guidelines for further FC driven buses will be established.

A MAN low-floor bus, model NL 263 FC, was equipped with the components for a fuel cell drive system. The PEM fuel cell was developed by the power generation division of Siemens. Four fuel cell modules deliver a net electrical output of 120 kWe to the two electric motors (2x75 kWe), which are linked by a summation gearbox (manufactured by the Siemens Transportation Systems Division). MAN Technologie AG was responsible for integrating the compressed hydrogen storage system, which allows for a driving range of around 250 km. Linde AG took care of the hydrogen auxiliary systems and delivered the compressed gaseous hydrogen for the test operation in the cities of Nuremberg, Erlangen, and Fürth between October 2000 and April 2001. Ludwig-Bölkow-Systemtechnik GmbH (LBST) coordinated the project.

The project was divided into four phases. The conceptual design phase was completed in 1997. The four PEM fuel cell modules by Siemens were built, tested, and integrated into a dummy of the rear truss frame of the bus to check integration-related implications. This system integration phase ended in 1999. The transfer of the entire propulsion system into the final bus body was completed during the first quarter of 2000. The subsequent testing and commissioning phase continued through the second quarter of 2000. The Nuremberg traffic authority (VAG) conducted the public test operation of the bus between October 2000 and April 2001. The general data on the bus project can be found in the Internet at http://www.fuelcellbus.com [1] and at http://www.wiba.de [2].

2. GENERAL DESCRIPTION OF THE PROJECT

In 1994, a group of interested Bavarian industries initiated work on fuel cell propulsion for city buses and urban delivery vehicles. LBST, in collaboration with the industry partners and funded by the Bavarian State Ministry for Economic Affairs, Transport and Technology (BStMWVT), completed a feasibility study, which resulted in a set of detailed specifications required for such a project. In late 1996, Siemens Power Generation (KWU), Siemens Transportation Systems, MAN Nutzfahrzeuge, MAN Technologie, and Linde began developing a fuel cell city bus prototype. The 7.5 million € project received 50% funding from BStMWVT, through the Bavarian Hydrogen Initiative. It was coordinated by LBST. The preparation and progress of the project are documented in several publications [3]–[6].

The PEM fuel cell system was integrated into a regular low-floor city bus. The electric energy from the fuel cell is fed to two asynchronous motors, which transmit power to the rear axle via a summation gearbox and a cardan shaft. Hydrogen is stored under pressure in composite-material bottles with inner aluminum liner.

3. DESCRIPTION OF THE COMPONENTS

3.1 The concept

A conventional low-floor city bus was equipped with a fuel cell system delivering electricity to an electric drive train. The hydrogen is stored on-board the vehicle in compressed gaseous form. A schematic picture of the bus is shown in Figure 1, the propulsion system and the peripheral components and subsystems are outlined in Figure 2, and a summary of technical data is shown in Table 1.

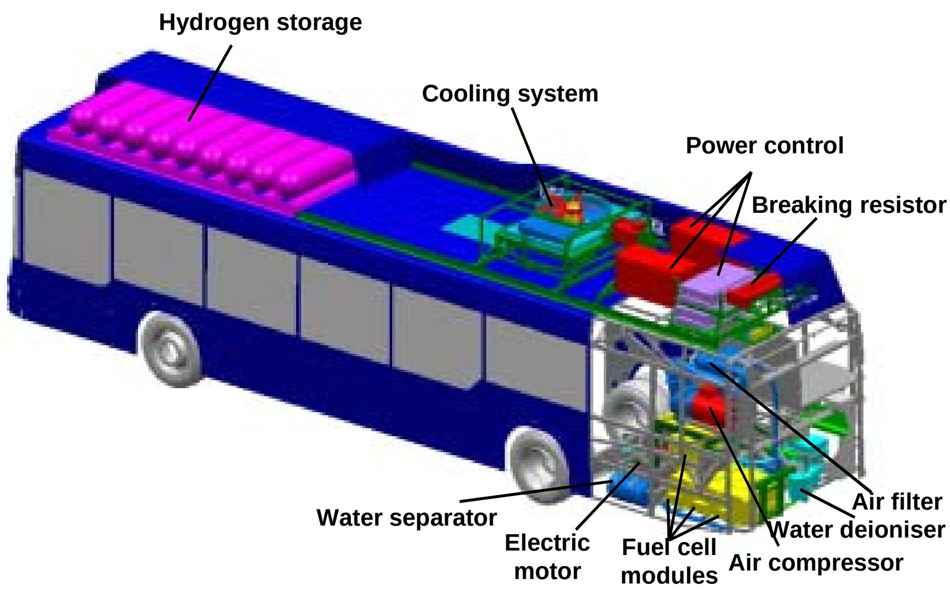

Figure 1: 3-D schematic of the MAN PEM Fuel Cell City Bus

3.2 The bus

A MAN low-floor city bus was adapted to fuel cell propulsion. The fuel cell system was housed at the rear of the vehicle. The 12-m fuel cell bus, NL 163 BZ, has a maximum total weight of 18 tons.

In addition to housing the various components of the fuel cell drive, the modified bus design required attention to the choice and design of the auxiliary power consumers normally driven by hydraulics, e.g. brakes, doors etc. Here, everything is electrically driven.

3.3 The fuel cell

The fuel cell system is a PEM (proton exchange membrane) fuel cell system manufactured by Siemens Power Generation (KWU). It consists of four modules each delivering 30 kW rated output power at a voltage level of 400 V at maximum output. The fuel cell operates at a temperature of 60°C, an air pressure of 1.5 bar (abs.), and an air ratio of 2. The hydrogen consumption at rated output is 8 kg/h.

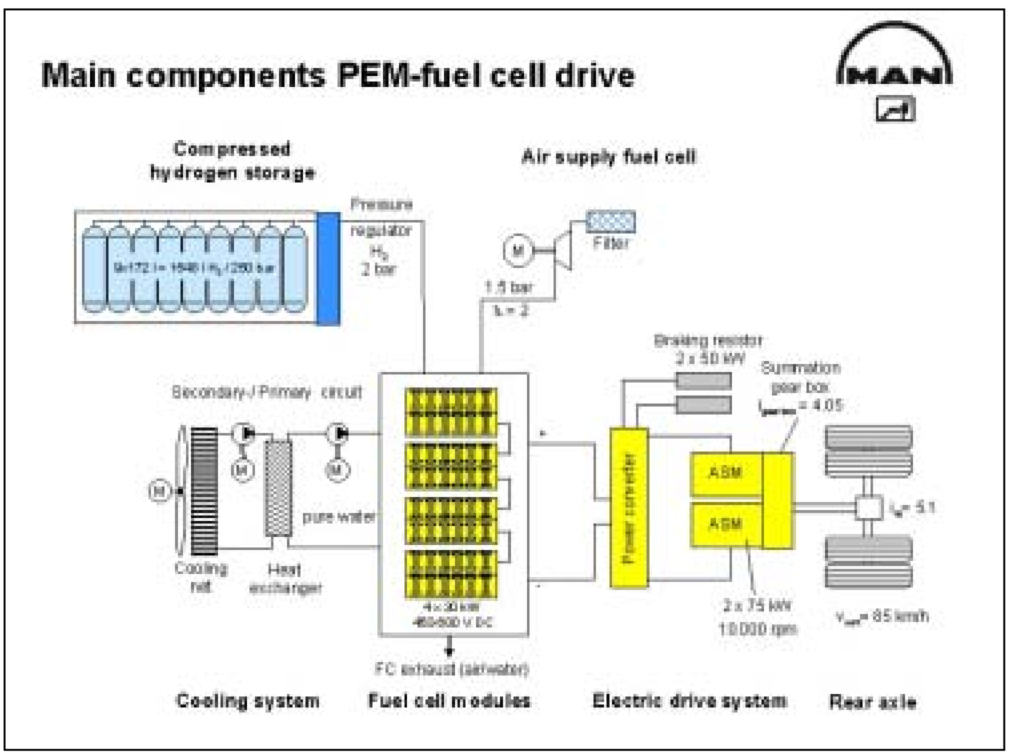

Figure 2: Diagram with main components of the MAN PEMFC city bus

3.4 The electric drive

Two asynchronous motors, which transmit their power to the rear axle via a summation gearbox and a cardan shaft, propel the bus. The electric motors have a maximum output of 75 kW each. A pulse-controlled inverter transforms the DC current from the fuel cell for the electric motors.

3.5 The hydrogen storage

The hydrogen is stored on-board the bus as a compressed gas, at a pressure of 25 MPa, in nine pressurized cylinders. The cylinders, which are manufactured by Dynetek, are fabricated from a composite material and lined with an inner aluminum liner. Together, the cylinders have a total capacity of about 1.55 m^3 [approx. 30 kg of H_2], which gives the bus an operating range of some 250 km.

Table 1: Summary of technical data

Task / Subsystem	Industry Partner / Specifications
Project coordination	**LB-Systemtechnik GmbH**
Vehicle	**MAN Nutzfahrzeuge AG**
Type	Low floor bus NL 263
Length	12 m
Gross weight	18 t
Passenger capacity	56
Vehicle drive system	**Siemens AG, Transportation Systems**
ELFA drive system	2 asynchronous motors (1 PV5135), summation gear box
Max. output of traction motors	2 x 75 kW at 10 000 1/min
Traction motor converter	IGBT Pulse controlled inverter, type ELFADUO
Fuel cell system	**Siemens AG, Power Generation (KWU)**
Fuel cell modules	4 modules
Power output	120 kWnet
Voltage	450-600 V
Operating temperature	60°C
Operating pressure, air	≤ 1,5 bar abs
Air ratio	2
Hydrogen consumption at rated output	8 kg/h
Hydrogen storage system	**MAN Technologie AG**
Max. filling pressure	250 bar
Cylinders	9 Dynetek cylinders, aluminum-liner, compound with CFK
Total capacity	1548 l
Operating range	250 km
Hydrogen refueling system, Periphery	**Linde AG, Technical Gases**
Gas tract in vehicle	Pressure governor system
Hydrogen filling station	Storage, fuelling, including safety devices

4. INTEGRATION OF THE COMPONENTS

Siemens manufactured the four fuel cell modules in 1998. The four stacks together deliver a continuous gross power of 160 kW and can deliver a short-term peak power of 200 kW. The maximum net power of the fuel cell system is 120 kW (continuous) and 140 kW (short term).

To guide the systems integration work, MAN completed comprehensive simulations of the integration of all components. In 1999, Siemens began integrating the fuel cell system and the power train into a dummy of the rear truss frame of the bus to identify and address integration-related issues. A major problem with the electromagnetic compatibility of the various components was uncovered during the integration work. Once this problem was resolved, the fuel cell system, including the electric power train, performed satisfactorily in the dummy rear truss frame.

The fuel cell modules are situated in the lower left part of the rear of the bus. The air compressor, which delivers air to the fuel cells, is located in the upper left of the bus rear. These components are in a separate compartment, which is separated from the passenger space of the bus and blocks half of the back window. In future bus designs, smaller components and more advanced integration concepts will make it possible to integrate all components into the lower rear of the bus and on the roof, leaving the full space of the passenger compartment.

The electric motors, which are connected to the rear axle via a summation gearbox and a cardan shaft, are situated below the floor of the bus behind the rear axle. The power electronics, together with the breaking resistors, are located on the roof of the bus.

The cooling system consists of two circuits. The primary circuit cools the fuel cell modules and transfers the heat to the secondary circuit using a heat exchanger in the lower right of the rear of the bus. The secondary cooling circuit transfers the heat to the ambient air using a heat exchanger with blower fan located on the roof of the bus.

The bus auxiliary systems, such as the steering support pump and air compressors for actuating the doors are mechanically connected to and driven by the diesel engine in a conventional bus. In the fuel cell bus, these auxiliary systems had to be replaced by electric motor-driven systems. Commercially available electric motors, which can meet the requirements of the fuel cell bus auxiliary systems, are designed for stationary applications and are, therefore, far from optimized for transportation applications. This is one area where significant improvements can be achieved in the future, once when fuel cell power trains are established in series production.

The hydrogen storage system consists of nine pressure cylinders with a maximum pressure of 25 MPa and a total geometric storage volume of 1,548 liters, allowing for a driving range of about 250 km. Similar to natural gas-powered buses, the storage system is located on the front part of the roof of the bus. Due to the size of the fuel cell system and the permissible rear axle load, no additional weight was allowed. The filling hose is located on the right hand side of the bus in the front. A valve box and a pressure reduction unit are located directly adjacent to the storage system, from where low-pressure hydrogen is delivered via a pipe to the fuel cell.

The transfer of the fuel cell system and the electric power train from the dummy rear truss into the bus was completed in April 2000. Then, the bus received its seats and the outer design.

The first public appearance of the bus was on May 8, 2000 at the Bavarian Fuel Cell Day, which was organized by the Bavarian Ministry for Economy, Transport, and Technology. Subsequently, the vehicle underwent a comprehensive testing and commissioning phase. The second and third public appearances of the bus were in September 2000, at the HYFORUM 2000 in Munich and then at the heavy-duty vehicle International Automobile Fair in Frankfurt. The public demonstration of the bus with VAG, the local operator, started on October 20, 2000, in Nuremberg.

5. PERFORMANCE

Efficiency data on the fuel cell stack, fuel cell system, and fuel cell drive system are depicted in Figure 3. The PEMFC-electric drive system has a superior efficiency compared to the diesel system when utilized at 75% of its design capacity. At part load its efficiency advantage lies between 20% and 30%, thus providing improved fuel efficiency in typical urban stop-and-go driving patterns (see Figure 4). The fuel cell-powered bus is also a zero pollutant emission system with drastically reduced noise emissions. The good tank-to-wheel energy efficiency for the city bus is shown in Figure 5. Compared with other heavy-duty vehicles, the PEMFC-driven city bus achieves the best fuel economy, i.e. better than long-haul heavy-duty trucks, which have very efficient diesel engines and operate more often at almost full engine design capacity. On the other hand, the tank-to-wheel fuel economy advantage for passenger cars is even higher and reaches up to 50% for PEMFC versus diesel drives.

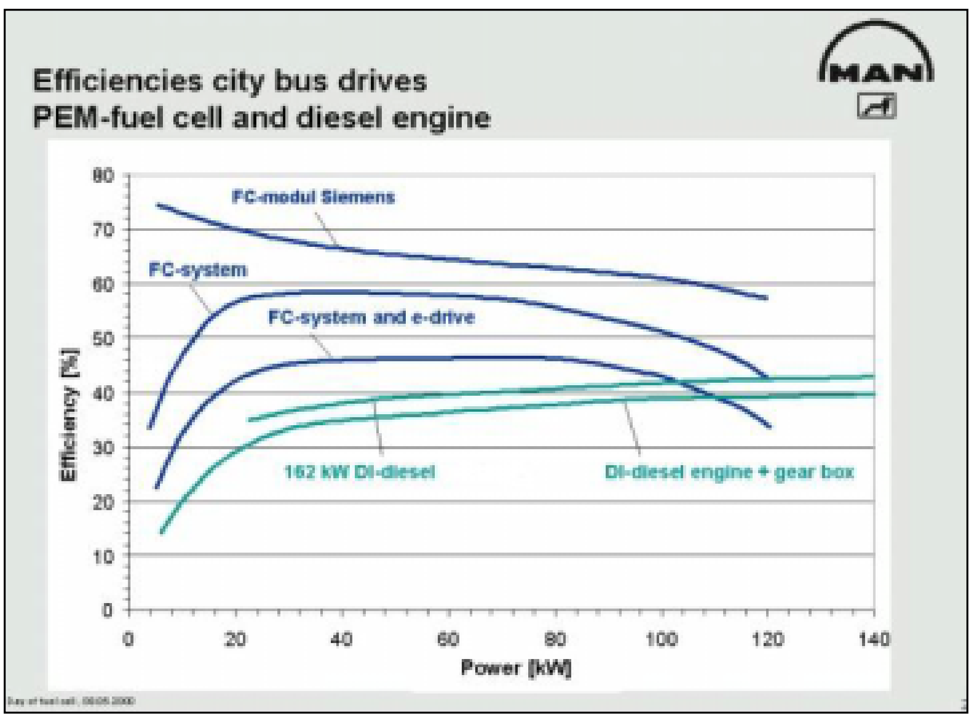

Figure 3: Efficiencies of PEMFC electric drive versus conventional diesel hydraulic drive system

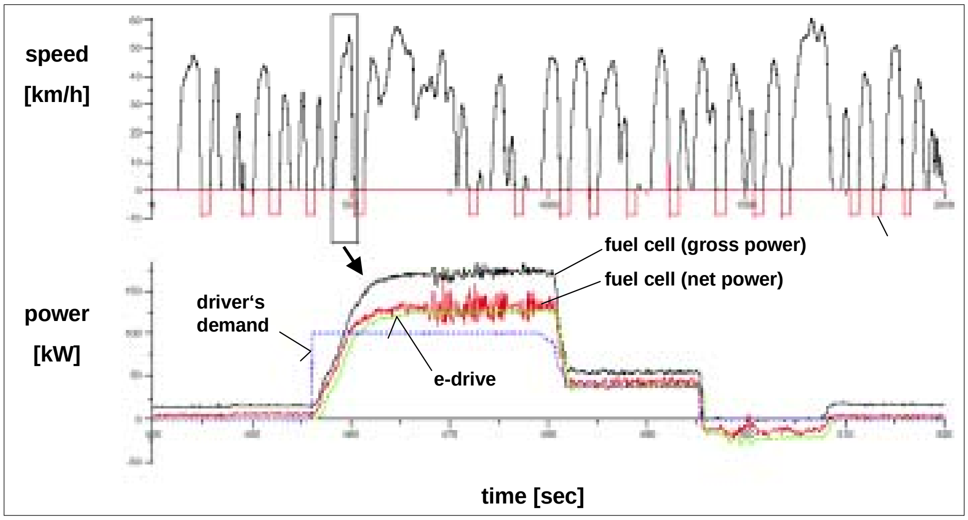

Figure 4: Typical 'power/time' diagram for fuel cell electric drive operation in urban environment [FC-bus in operation in Munich (18 t) - route Obermenzing - Ratzinger Platz]

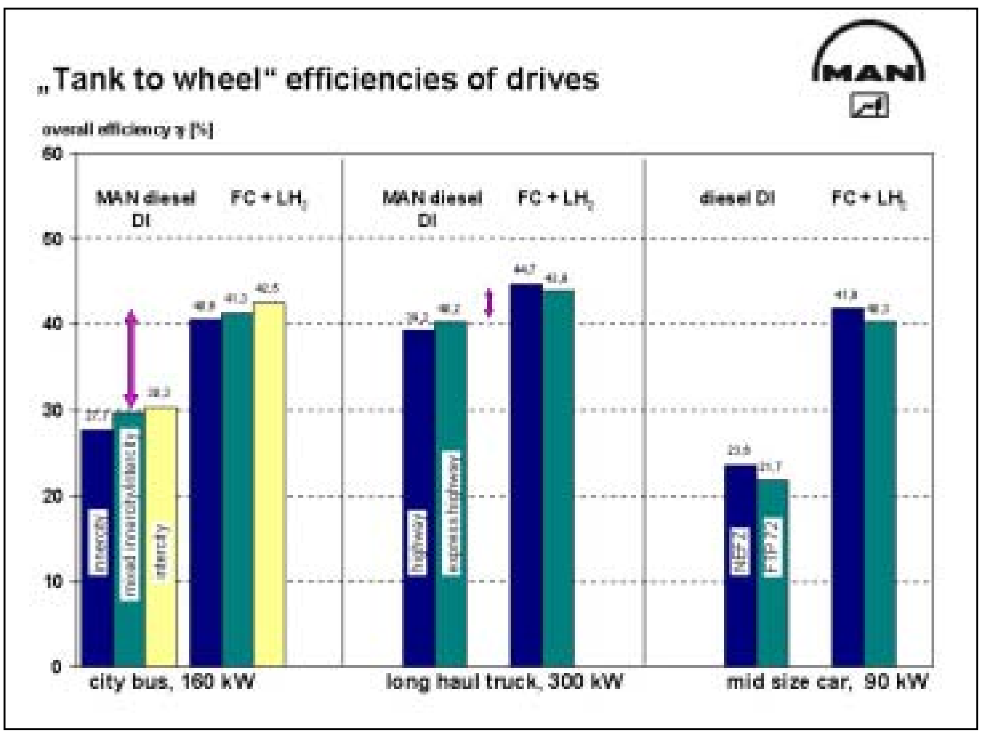

Figure 5: Overall tank-to-wheel efficiencies of PEMFC and Diesel drive systems

6. OPERATIONAL EXPERIENCE

The demonstration of the fuel cell bus prototype in public revenue service took place in Nuremberg from October 2000 to January 2001, in Erlangen from January to mid-March 2001 (interrupted by a one week presentation in the Swiss city of Berne), in Fürth from mid-March to April 6, 2001, and again in Erlangen from April 6 to April 18, 2001. During this half-year demonstration period the vehicle accumulated some 8,000 km of operation.

LBST developed a questionnaire on the experience obtained by the operator VAG. The answers by the operator are summarized as follows:

- The operation on the VAG network was extremely successful, with a large positive public relations impact in the greater Nuremberg area, and with great interest by the bus passengers and the VAG employees.
- A significant disadvantage of the bus is the lack of space for standing passengers, which is attributed to the prototype character of the bus. Technical problems were encountered with the central hydrogen shut-off valve at the tank storage system, which caused difficulties in storing the bus in the bus depot over night (there was a repeated need to close all individual valves at the storage containers). Bus operation was limited during times of freezing ambient temperatures due to the pure water contained inside the fuel cell system. The system's control modules, designed for stationary use, failed several times. Also, conventional technical components such as the electric drive motor and the refrigerant pump failed. With respect to these problems, the operator, VAG, sees the need for additional development efforts in order to allow timely limited parking outside and unlimited operation at all temperatures.
- No differences were observed by the drivers with respect to the handling of the bus compared with diesel buses. The increased bus height must be accounted for in the route planning. The much higher dead weight must be reduced drastically in order to allow higher transport capacities. As technology improves, adjustments in the interior layout are also expected. In general, the prototype refueling station is more complicated than the diesel version and represents a significant cost factor, similar to CNG. The hydrogen supply must be improved with respect to supply security and refueling station redundancy to the level of today's diesel stations. The refueling procedure of the prototype filling station is acceptable, although the refueling times should be reduced. The bus drivers themselves performed the refueling after the filling equipment manufacturer (Linde) instructed the drivers in the system's operation. Supplying hydrogen through compressed gas bottle trailers was not regarded as a suitable solution beyond the present experimental demonstration phase. The maintenance advantages, which can be expected from the electric driveline, may be compensated for by the effort required for the gas storage system. Due to the new technologies, different and greater requirements for workshop personnel must be assumed.
- All project partners were very open-minded. The personnel acted without any reservations and the bus drivers could handle the vehicle very well. The service personnel, who were dedicated only to servicing the conventional parts of the vehicle (not the fuel cell relevant parts), encountered no problems.
- The approval authorities supported the operator VAG in a very cooperative way via consultation and by granting the necessary approvals quickly.

- During the bus demonstration period, active communication between the passengers and the drivers occurred. Passenger interviews were performed in Erlangen and Nuremberg.
- The public was very interested in the project. The press, media, city administration, and city council were intensively involved (official inauguration of the bus and press conference in Nuremberg, presentation at the Nuremberg innovation days, hand-over of the bus to the mayors of Erlangen and Fürth, many print media publications and telecasts).
- According to the operator VAG, the future application of hydrogen fuel cell buses has to be measured against standard diesel bus cost due to competition. Environmental benefits and advantages for the bus passengers (pollutant and noise emissions, interior design, riding comfort) must compensate for additional costs. Probably these quality improvements will need to be supported financially with public incentives. The same may be true for the more expensive refueling infrastructure.
- From the operators viewpoint, the most important technical questions to be solved are: significantly reducing dead weight, reducing operating costs as close as possible to diesel bus operating costs (which requires taking into account the fuel production and supply chain), storing the bus inside the depot (probably requiring supervising systems such as sensors), reducing interior noise levels due to improved auxiliary systems such as heating and ventilation, recuperating energy in order to reduce fuel consumption, improving dimensioning of fuel cells, increasing suitability for operation under winter weather conditions, improving general availability, and realizing more efficient gas storage.

7. ENVIRONMENTAL ASPECTS

In assessing the environmental benefits of fuel cell vehicles, the analysis of the full fuel cycles, i.e. from cradle to grave, in this case from bore hole to tailpipe, is of major importance. Energy efficiency and carbon dioxide emissions are not only important in the operation of a vehicle, but also in the production, delivery, and conditioning of the fuel itself. This is especially true for renewable fuels thus showing their full potential for mitigating global warming and resource problems.

Other problems associated with road transportation are summer smog/ ozone and poor general air quality—especially in urban areas. But zero emission fuel cell drives can lead to substantial improvements. As with the energy efficiency/CO_2 analysis, local emissions from fuel production and distribution also have to be taken into account. For heavy duty vehicles like buses, nitrous oxides and particulate emissions are the most important and critical emissions for urban air quality.

In collaboration with the project partners, LBST has analyzed full fuel cycles.

The analysis of fuel production and distribution has been carried out using the E2-database [7]. In addition to the analysis tool, the GEMIS tool [8] provides data on a variety of energy chains, processes, scenarios etc. with different levels of sophistication and detail. For this analysis, several new energy chains and processes, especially those for hydrogen and methanol production, were incorporated by LBST. Energy efficiency and emission data are based on manufacturer information and other studies and inventories.

Seven different combinations of propulsion systems and fuels have been analyzed:

1. diesel internal combustion engine; no exhaust gas catalyst; low sulfur diesel
2. internal combustion engine; compressed natural gas
3. hydrogen fuel cell drive; compressed hydrogen production by natural gas steam reforming
4. hydrogen fuel cell drive; liquid hydrogen production via electrolysis from Canadian hydro power
5. methanol fuel cell drive; onboard methanol steam reformer; methanol production from natural gas
6. hydrogen fuel cell drive; compressed hydrogen from biomass farming and steam reforming
7. methanol fuel cell drive; onboard methanol steam reformer; methanol production from wood

The seven fuel chains have been assigned to different time horizons depending on their technical and commercial maturity. The indicated time scales are not to be taken as predictions of the commercial availability, but are rather intended to give a qualitative ranking of the options:

short-term (0 to 5 years)	diesel (1), natural gas (2)
mid-term (5 to 10 years)	fuel cell + hydrogen from natural gas (3) fuel cell + hydrogen from Canadian hydropower (4) fuel cell + reformer + methanol from natural gas (5)
long-term (10 years and up)	fuel cell + hydrogen from biomass (6) fuel cell + reformer + methanol from wood (7)

A 12 m low-floor city bus was chosen as the vehicle for the comparison. Energy consumption of some of the vehicle/fuel combinations was simulated using the so-called „Linie 66“ driving cycle, a synthetic driving cycle for city buses in the city of Munich. For other options, the fuel consumption has been estimated based on simulations of similar vehicle concepts and on the experience of the bus manufacturer MAN Nutzfahrzeuge. Emissions were estimated based on projected emission standards for Europe (EURO 3) [9].

The results for the full fuel cycles are shown in Figures 6 and 7. The data used in the analysis represent conservative estimates for the non-conventional options.

Figure 6 shows the energy consumption of the various options in units of kWh/100 km (diesel has an energy content of roughly 10 kWh/l). Over the whole fuel chain, only the “hydrogen from natural gas fuel cell vehicle“ (3) and the “hydrogen from biomass farming fuel cell vehicle“ (6) are about as energy efficient as the diesel vehicle. The other vehicles are less energy efficient.

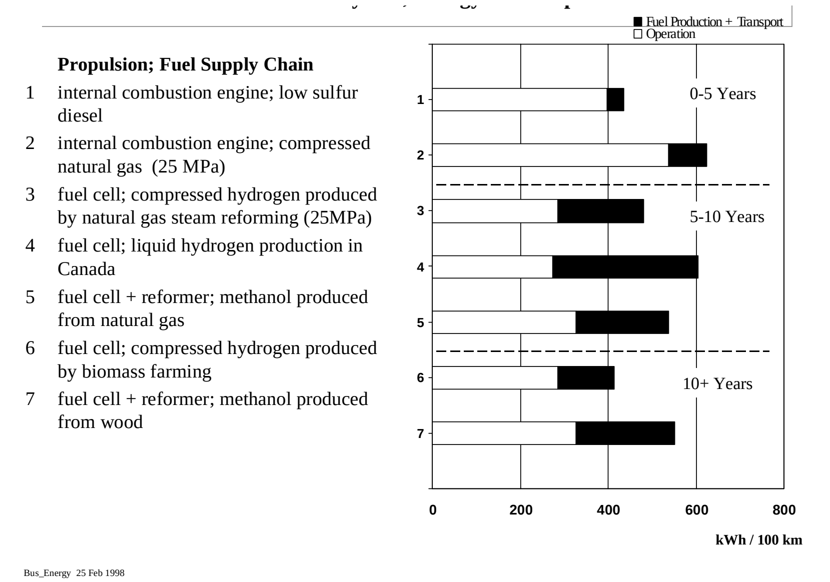

Figure 6: Energy consumption of low floor city bus

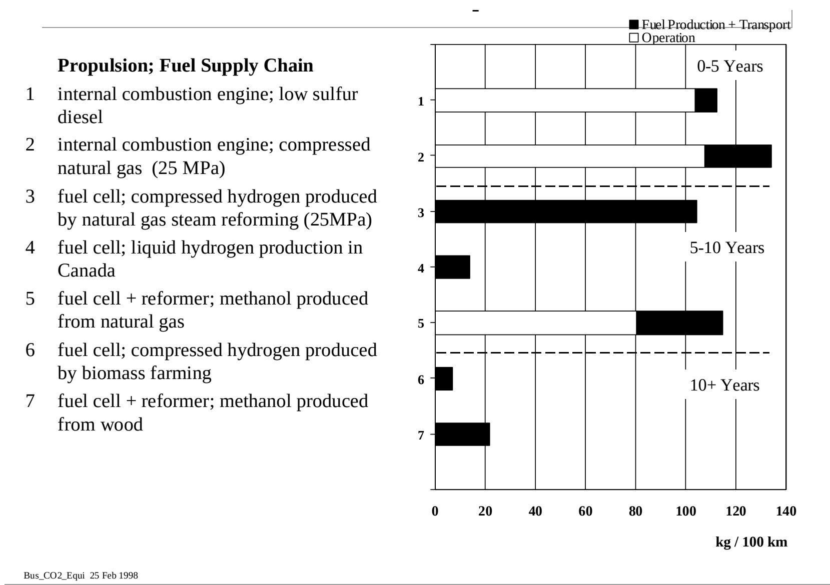

Figure 7: Emissions (in CO_2-equivalent) of low floor city bus

Introducing renewable fuels, however, reduces the importance of energy efficiency in the fuel production and supply chain. Carbon dioxide emissions are of much greater concern because they cause global warming. Other trace gases contributing to the greenhouse effect are methane (CH_4) and nitrous oxide (N_2O). Based on CO_2 equivalence factors of 21 for methane and 310 for N_2O (atmospheric lifetime in both cases: 100 years), the CO_2 equivalent was calculated and indicates the global warming potential of the different vehicle concepts. Results are shown in Figure 7. CO_2 absorbed from the atmosphere by the biomass used for fuel production has been subtracted from the CO_2 emissions during fuel production and fuel consumption in the respective fuel chains. Here it is obvious that even though some of the renewable fuel chains are not as energy efficient as diesel, the former have a by far greater potential for reducing greenhouse gases than any increase in conventional fuel efficiency. This is to a large extent due to the fact that propulsion systems for buses are already very energy efficient; the case for passenger cars is somewhat different. This shows that only the introduction of renewable fuels can significantly reduce the greenhouse effect caused by duty vehicles. Nevertheless, the “hydrogen from natural gas fuel cell bus“ offers slight improvements compared to a diesel bus. Technical development will probably increase the advantage of this vehicle concept further.

Emissions of nitrous oxides responsible for ozone formation can be reduced by a variety of alternative fuel/vehicle concepts. Already, compressed natural gas drives can reduce the nitrous oxide emissions by a factor of four. Most of the fuel cell drive/ fuel combinations have the potential to reduce these emissions by another factor of four. However, NO_x emissions of diesel engines might be reduced through the use of reducing catalyst converters (deNOx catalyst converters). Ozone formation is a regional problem. Therefore, nitrous oxide emissions from fuel production and distribution in the region of consumption must be taken into account.

Another local air quality problem caused by duty vehicles are particulate emissions, which may cause lung cancer. Here also, a variety of alternatives to diesel vehicles offer substantial improvements. In addition, filter systems for diesel vehicles are presently being developed. Particulate emissions are mainly a local problem, especially in urban areas, so the particulate emissions in the fuel production and supply chain might not have as negative an effect as those stemming from bus operation.

The analysis of full fuel cycles shows that the fuel cell drive for city buses offers significant environmental improvements compared to diesel internal combustion engines. This refers to emissions of greenhouse gases as well as to local emissions of trace gases. Because the next emission standards in Europe for diesel engines from 2005 (Euro 4) and 2008 (Euro 5) [9] will require further improvements, especially of nitrous oxides and PM, the main interest in emission reduction will concentrate on greenhouse gas reduction. This goal only can be achieved by introducing renewable based fuels.

8. PUBLIC ACCEPTANCE

Sample interviews were conducted among bus passengers during their bus rides in the period of 04-06 April 2001 and some 156 passenger opinions and judgments were collected. The reactions encountered were generally very positive. Two-thirds of the passengers interviewed had already noticed the drastically reduced exterior noise level when the bus approached the bus stop. Also the majority of the bus riders perceived the noise level inside the bus as very low. When asked about the technology employed for the propulsion of this quiet bus, almost 90% of the riders could not imagine or explain the functioning principle and expressed an interest in obtaining further information. Due to the zero pollutant emissions and the very low noise emissions, the response to further public financial support for such technologies was positive. Most passengers advocated an extended use of such clean buses even if moderate ticket price increases would be the result. The commitment of the operator VAG to the field of clean hydrogen fuel cell buses was welcomed. The customers praised the level of innovation and the active protection of the Nuremberg environment shown by the bus demonstration. Also the interior equipment of the test bus, which represented the new design of the new generation of VAG buses, was overwhelmingly well received by all riders.

Several general conclusions can be drawn from the results of the extensive hydrogen acceptance study performed during the demonstration of an internal combustion engine hydrogen city bus in Munich in 1997 (http://www.HyWeb. de/accepth2/) [10].

- First of all, and most importantly, hydrogen technologies enjoy a high level of acceptance among hydrogen bus passengers and among secondary school students in Germany. People are in favor of the further development of hydrogen technologies, they support their deployment and they see their environmental benefits. Even though people expressed a certain fear of explosions in hydrogen technologies, the study does not reveal potentially severe acceptance problems. It is noteworthy that hydrogen is very rarely associated with danger spontaneously; only when people are asked to assess the risk of explosions do they tend to see a certain risk.
- It can be stated clearly that, in contrast to most hydrogen experts' opinion, people do not associate hydrogen with past accidents or catastrophes such as the Hindenburg disaster. At least in Germany, hydrogen is almost free of this negative burden.
- The study shows a general tendency towards higher acceptance of hydrogen technologies when people are in direct contact with them. School students interviewed in the bus made significantly more positive evaluations than students in the classroom.
- Other items do not have such a clear influence on the level of acceptance of hydrogen technologies; a high priority given to environmental issues and a high level of knowledge on hydrogen only have a weak positive influence on the acceptance.
- The test of hydrogen knowledge of school students showed that the general level of knowledge is rather poor. The bus passengers, half of whom had not had information about hydrogen before, confirm this result. At the same time, people are interested in knowing more on the subject.

In conclusion, it can be stated that both direct contact with hydrogen technologies such as taking a hydrogen bus, and learning about hydrogen technologies at school have a significant positive effect on people's acceptance of hydrogen technologies. At the same time, knowledge of hydrogen technologies and its environmental advantages is not widespread. Hydrogen is not spontaneously associated with danger or with past accidents.

9. MAN EXPERIENCES DURING DESIGN AND INTEGRATION PHASES

Just like the first automobiles, fuel cell buses have not yet achieved a standard design. The few prototypes in existence worldwide show a wide range of technical solutions, because of the non-existent automotive supplier base. MAN had the favorable position of having developed compressed hydrogen storage and electric drive systems already proven in other applications. The storage system relies mainly on series-production CNG technology, and requires special tests and permits from the safety authorities. Integration and operation of this system have been problem-free. The electric drive system uses motors and converters already developed for diesel-electric, trolley- and hybrid-drives. With minor changes this technology was readily operational.

For the fuel cell system test and integration, a standard rear-end space-frame of the bus was incorporated with all the interfaces and modifications using 3D-CAD.

Siemens integrated the system and performed a number of bench tests with an external cooling system and an electric load simulating the electric bus drive. The tests led to a number of system modifications. After demonstrating stable long-term operation under full load at the Siemens facility, the system was approved by Siemens and MAN for this trial application.

Integrating the hardware in the bus was almost immediately successful. During the start-up and preliminary testing phase additional system modifications were carried out. After solving a number of electromagnetic compatibility (EMC)-related problems and bus finishing, the prototype was “rolled out” after just three months of intensive integration and testing work.

As mentioned above, the components and auxiliaries were produced according to standards defined for chemical industry and other stationary surroundings. In many cases they do not fulfill specific automotive requirements. To bring down costs and increase reliability, a great deal of development is still needed.

10. FUTURE POTENTIAL, FUTURE PLANS

MAN expects series application of fuel cell buses beginning in 2008. Experience shows that the series production of the buses will also lead to cost reductions and to achieving market conditions. MAN has pursued hydrogen city bus development for almost one decade (see Figure 8) and is continuing its fuel cell bus activities with a second-generation fuel cell bus already in progress. A third generation is in the planning stage for the 2nd phase of the Munich Airport Hydrogen Project. In addition to the design and development of the vehicles and drives, the production and distribution of hydrogen as a fuel will strongly influence the phase of implementation. Success depends on the agreement of the major vehicle producers and energy suppliers concerning the fuel choice. Accompanying activities such as the Transport Energy Strategy (TES) are needed to overcome market barriers during the introduction of hydrogen.

The public transport operator VAG sees an immense future potential for hydrogen fuel cell buses in urban passenger transport once vehicle and infrastructure costs are reduced to economically acceptable levels. Because it is reasonable to use renewable energy sources to reduce CO2 emissions, this bus technology is viable.

11. CONCLUSIONS

The accumulated experience of driving the bus of some 8,000 km over five months lies within the range of the 42,000 km achieved by the ICE city bus operated by MAN between 1996 and 1998 in Erlangen and Munich [11]. These driving experiences also compare well with the two Ballard PEMFC transit bus trials in Chicago and Vancouver, in which buses accumulated similar operating ranges.

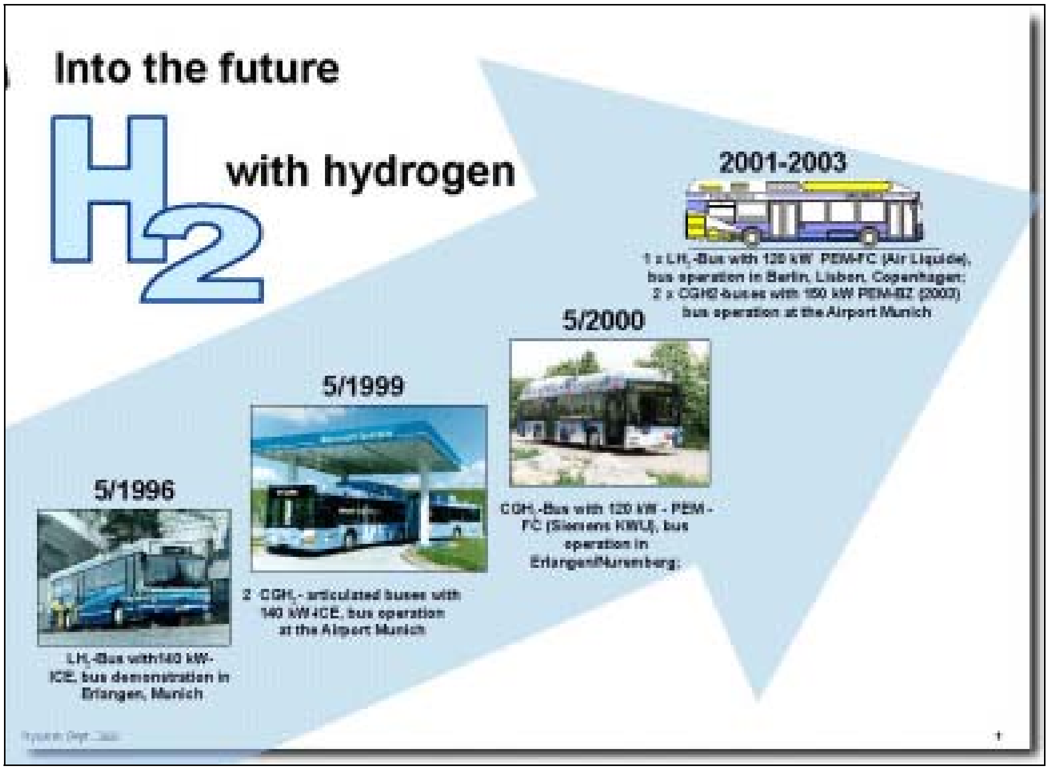

Figure 8: Roadmap of hydrogen bus development at MAN Nutzfahrzeuge AG since the early 1990s

Acceptance by the customers—the bus passengers—was overwhelmingly positive, resulting in requests for more hydrogen fuel cell type buses to be placed in service as early as possible.

Very valuable experience in fuel cell system integration was acquired by MAN Nutzfahrzeuge enabling them to continue advancing this type of vehicle propulsion concept.

Therefore, MAN, together with its partner Air Liquide, is already finalizing a second PEMFC bus with financial support by the European Commission. This bus will feature a hybrid electric drive system, most likely consisting of supercapacitors as the peaking device. The FC-system with a net power output of 120 kW contains three Nuvera stacks. Hydrogen will be stored in a LH_2 storage system from Linde. A one-year demonstration will take place in Berlin (nine months), Copenhagen, and Lisbon, starting in mid-2002 in Berlin.

Based on these two prototype fuel cell buses, MAN will develop and test several more PEMFC buses in the near future in order to develop the new drive system to a commercial product by the end of this decade. The 2nd phase of the Munich Airport hydrogen demonstration project will be the location for the test trials of the 3rd generation of MAN PEMFC buses. The two buses foreseen for this demonstration will include PEMFC systems supplied by UTC. In parallel, MAN will also pursue improved hydrogen ICE drivelines by developing new more efficient ICE concepts for hydrogen fueled city buses to be tested in the near future, e.g. in a project aiming at converting an entire feeder bus line in the south-eastern outskirts of Munich starting in 2003.

12. LITERATURE

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