Hydrogen Powered Fuel-Cell Buses Meet Future Transport Challenges

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Abstract

In view of the limited availability of fossil fuels and the necessity of reducing the output of emissions of greenhouse gases in the long term, the transport sector needs efficient, environmentally compatible drive solutions.
Hydrogen as a clean and sustainable fuel offers a high implementation potential and can be used both in internal combustion engines and in fuel cells. In urban deployment fuel cell drive has specific advantages and is suitable for use in city buses. Integration of low-cost electrical energy storage systems, e.g. supercapacitors, improves fuel consumption.
In May 2000 MAN presented its first fuel cell bus and will continue this development work with further vehicles. The first deployment of pre-series bus fleets with fuel cells using hydrogen as fuel can be expected from the end of this decade onwards.

Keywords: bus, efficiency, fuel cell, hydrogen, super capacitor, ZEV (zero emission vehicle)

1 The role of emissions and energy supply in the transport sector's future

The world's metropolises are continuously growing, and this trend will accelerate considerably in future. It is expected that by the year 2025, two-thirds of the world's population will be living in cities. In only fifteen years, there will be more than 350 cities with a population of more than one million [1]. Both the individual desire for unrestricted mobility and the expected growth rates of the metropolises will lead to traffic burdens with major effects on economic systems. Under these circumstances it will become more and more important to provide efficient and environmentally compatible public transport to cope with the demand for transport in urban areas. In the past reduction of the exhaust gas constituents subject to limitation - PM, NO_X, HC and CO - was a main reason for trying out and introducing alternative fuels and drive systems.

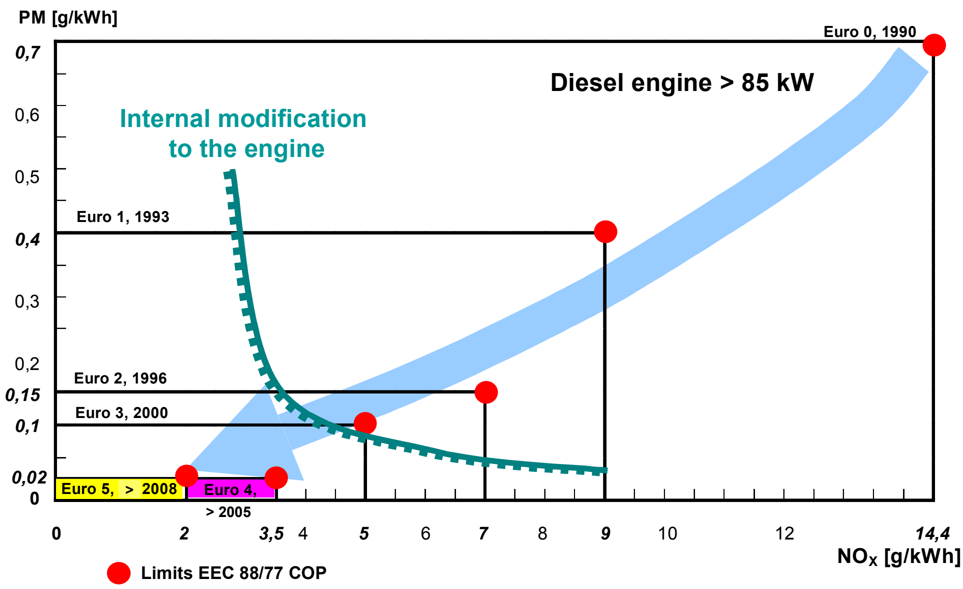

Fig. 1 On the way to minimal emissions of commercial vehicle drives

Low-emission, conventional internal combustion engines with highly developed exhaust-gas cleaning systems will in the next few years lead to further significant relief with regard to emissions in Europe. For commercial vehicles in Europe stricter emission limits, in particular for NO_X and PM, will be introduced in 2005 and 2008. Despite a higher transport performance in future, a fall in the total emissions of the constituents subject to limitation from the transport sector is expected [2].

These new technologies for diesel engines together with catalytic converters for passenger cars will reduce the overall emissions of road transport for particulate matter by a factor of 10 and for NO_X by a factor of 8 between the years 1990 and 2015. The German Ministry of the Environment and the German Environmental Agency consider the problem of Euro-Stage limited emissions as solved by Euro 5.

Road transport is a key element of the economic system of industrial countries today and will be in the future. In the next decades an increasing demand for crude oil, fig. 2, will be expected [3].
After the energy crisis of the 70s the industrial nations were able to create a counter balance to the oil sources in the Middle East by developing the oil fields in the North Sea and Alaska. However, these reserves only offer a short to mid- term secure supply [4].
Due to the fact that a decreasing number of new and large oil finds since the 60's the supply/demand gap from 2010 on, fig. 2, may have a negative impact on economic energy supply.

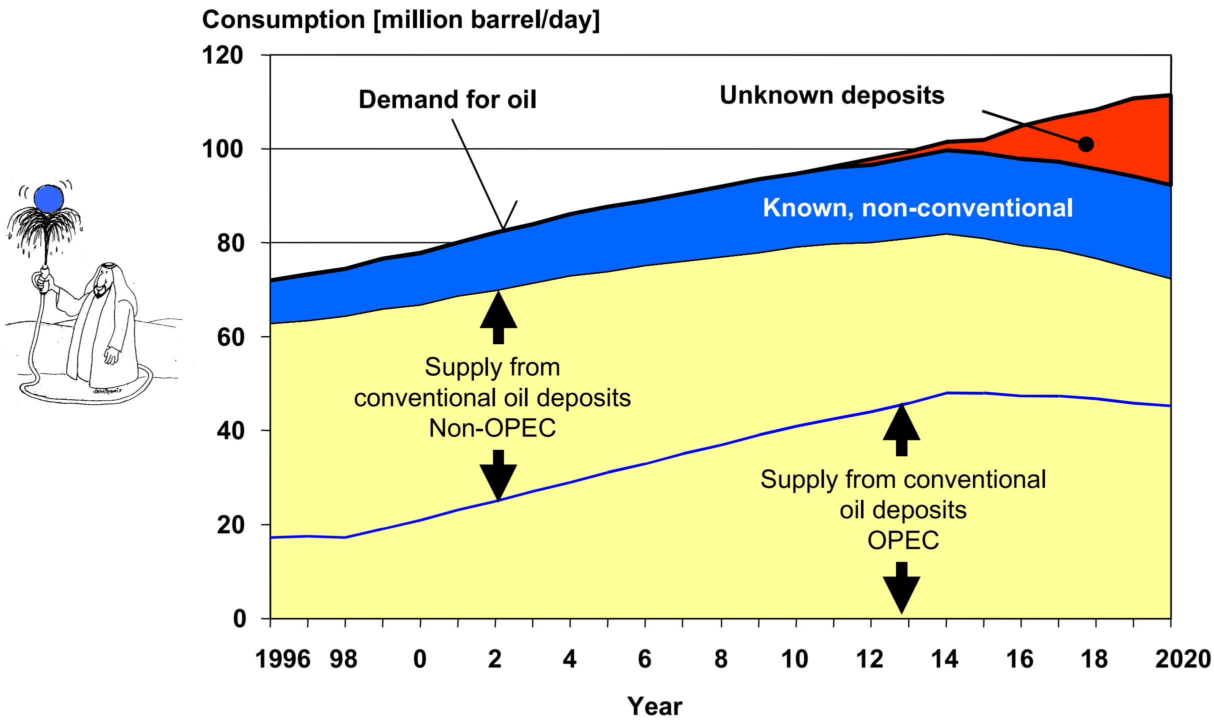

Fig. 2: development of world crude oil's demand and supply [3]

In MAN's view, hydrogen will become the fuel of the future with a high realisation and environmental potential. The long-term prospects for producing hydrogen without using fossil energy resources by electrolysis or from biomass in combination with innovative vehicle drive systems open up chances for reducing the transport sector's dependence on crude oil and cutting greenhouse gases.

There is no political movement in the EC towards a ZEV as regulated under Californian mandate. The EC sees CO_2 as the key factor which has to be considered in all sectors of the economy including road transport.

If fossil fuels are used, only a minor reduction in the output of CO_2 will be possible for commercial vehicles. With the growing demand for mobility, particularly in threshold countries, higher CO_2 emissions must be expected. Sources of energy with a lower carbon content indicate a solution to this problem.

2 Hydrogen - a source of energy with a future

Carbon-free fuel hydrogen can make a major contribution to a global reduction in CO_2 emissions.
A number of methods of producing hydrogen are available. Today, hydrogen is won predominantly for the chemical industry from fossil energy resources such as natural gas and heavy oil. Linked to fossil energies, CO_2-reductions depend on the efficiency of the production processes and the drive systems. Production processes which use biomass or electrolysis of water with electricity produced from regenerative sources offer nearly CO_2-free generation of hydrogen.

Hydrogen can be produced both in large plants and decentrally via small electrolyser outfits, which is an important advantage during the introduction phase for a new fuel.

In vehicles, hydrogen can be used in conventional internal combustion engines and in fuel cells in combination with an electric drive system. MAN is examining and assessing both forms of propulsion.

It has been shown since 1996 that hydrogen can be used successfully in internal combustion engines [5, 6].
Following development of a city bus with liquid hydrogen engine and its trials in regular service in Erlangen and Munich between 1996 and 1998, three further low-floor buses with internal combustion engine have gone into service at Munich Airport, fig. 3.

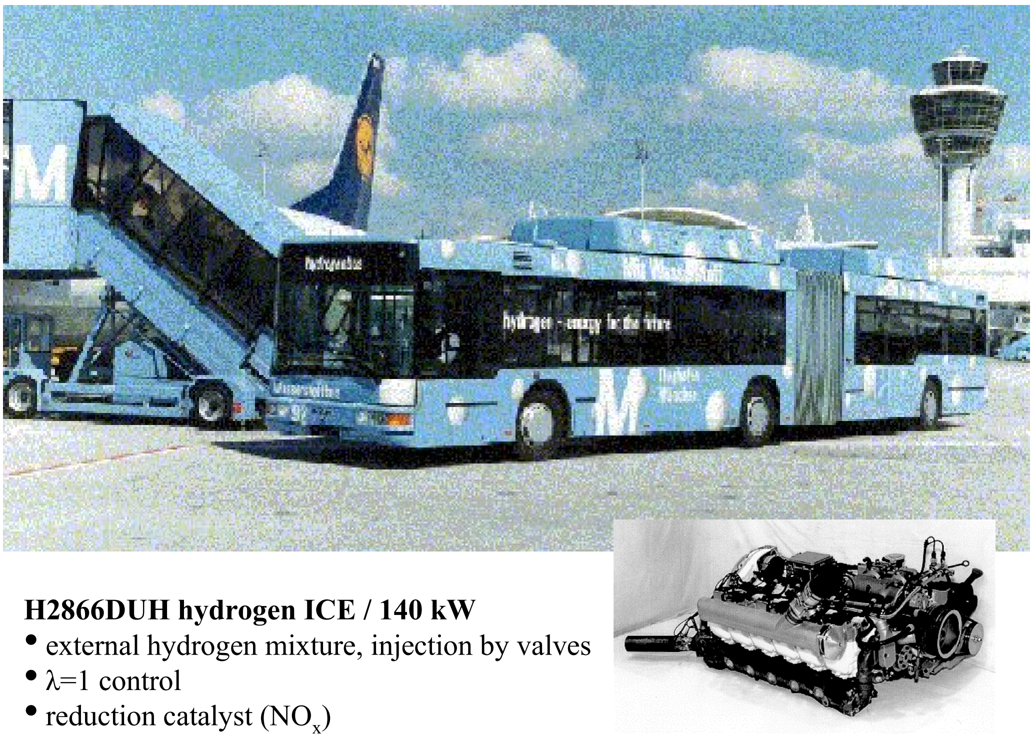

Fig. 3: Articulated bus with hydrogen-ICE in service operation at Munich Airport since 1999

These buses are fuelled with gaseous hydrogen. Since they went into service at the airport in the spring of 1999, they have covered some 40,000 km each and shown that they offer high availability for the bus operator.

3 Fuel cell drive – efficient propulsion for city buses

The fuel cell with its high specific efficiency in the partial load range has advantages over internal combustion engines in urban operation, fig. 4, and effectively reduces energy consumption in vehicle operation.
Compared to fuels containing hydrocarbons, which have to be converted to hydrogen via reformer systems and cleaned of CO before being used in the fuel cell, direct use of hydrogen offers maximum energy efficiency in the fuel cell system.

In case of onboard storage of methanol the tank-to-wheel efficiency would be at the same level as with the diesel ICE but costs for the drive system much higher. The main disadvantage of hydrogen storage is the lower energy density leading to higher volume requirements in the vehicle. Fleet operating city buses with limited cruising radius offer sufficient volume for hydrogen storage on the roof.

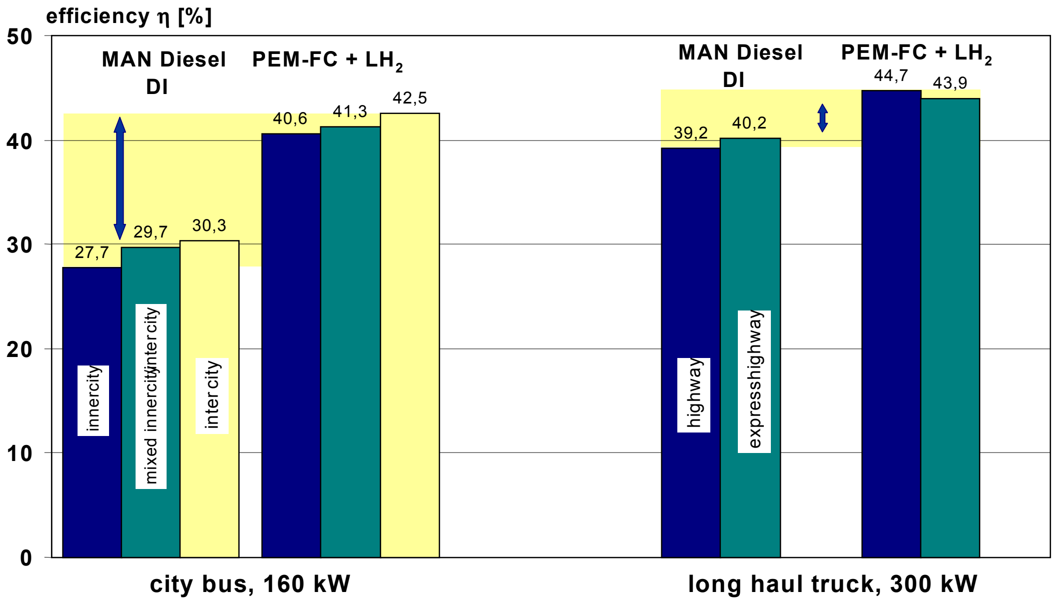

Fig.4: tank-to-wheel efficiencies of direct injection diesel compared with PEM-FC/LH_2 propulsion

4 MAN's first low-floor bus with fuel cell propulsion

The bus was developed with Siemens and Linde as part of the Bavarian Hydrogen Initiative and co-ordinated by Ludwig-Bölkow Systemtechnik [7]. The zero emission bus was presented in May 2000 and represents a further milestone along the road to the hydrogen-based economy.

The Bavarian State Ministry for Economic Affairs, Transport and Technology supports the development and introduction of new drive technologies, thereby aiming to achieve a considerable reduction of exhaust-gas and noise emissions in traffic and, in the long term, preparing to convert to clean, renewable sources of energy.

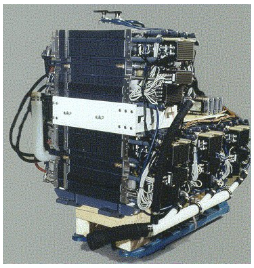

Fig. 5:
MAN’s first fuel cell bus in operation in Erlangen, Nuremberg and Fürth, powered by four fuel cell stacks;

The bus is based on a modern low-floor vehicle with the model designation NL 263. The PEM fuel cell system, built by Siemens Power Generation, contains four fuel-cell stacks connected in series with a total of 640 individual cells and the peripheral supply system.
The power electronics convert the direct current from the fuel cell to alternating current and regulate the output for the electric drive system, fig. 6.
Two Siemens asynchronous motors linked mechanically via a summation gearbox drive the series-production rear axle directly. The concept of the electric central drive unit makes use of proven, low-cost components from the range of modules available for MAN buses. The drive system guarantees operating ranges necessary for city buses and demonstrates comfortable and low-noise propulsion

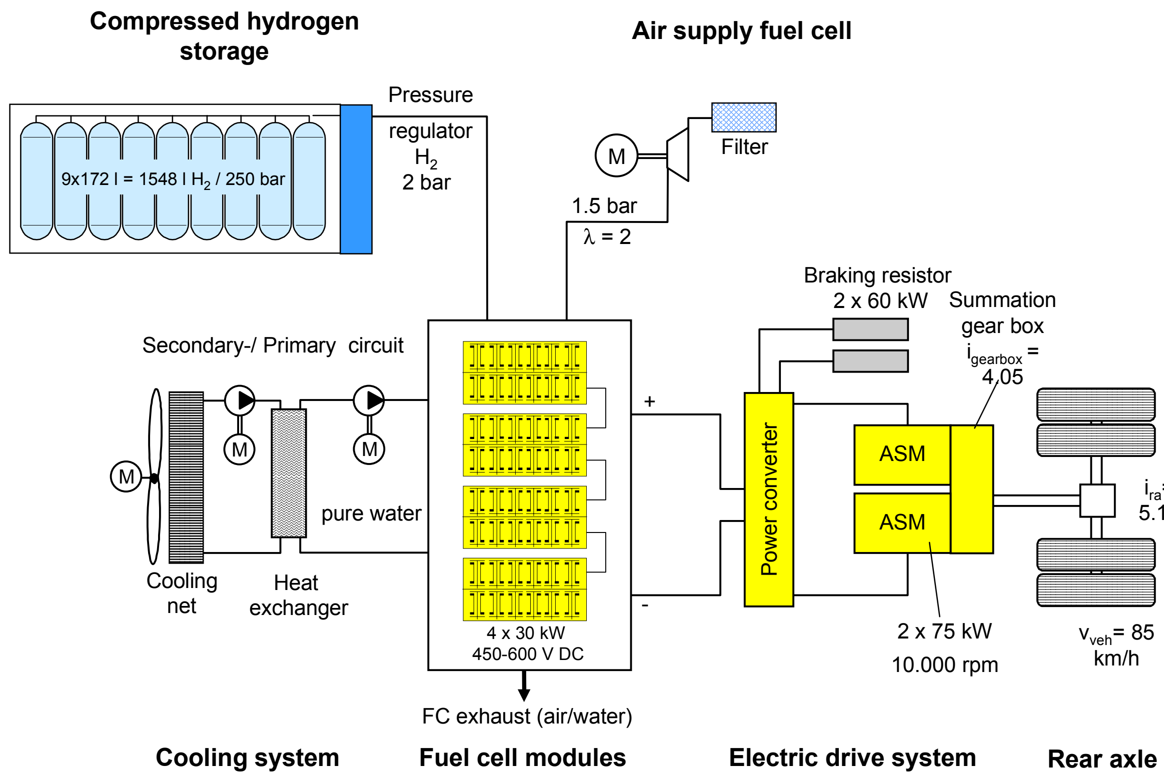

Fig. 6: Main components of the low-floor bus with Siemens fuel cell

In the vehicle, the bus standard electrical system and the DC network with approx. 450 - 600 V from the fuel cell are available for powering the drive system, fig. 6, and auxiliary units.

On board the vehicle, the hydrogen is stored as compressed gas in a system developed by MAN Technology. This system consists of nine tanks, each with a capacity of 172 l. To keep the weight of the storage system down, the pressurised tanks are made of an aluminium liner and a full carbon-fibre winding. The storage system has a maximum pressure of 250 bar, a total capacity of 1548 litre hydrogen and is mounted similar, as in standard natural-gas buses, on the roof of the vehicle. The 28 kg of hydrogen corresponds in terms of energy to approx. 100 litre of diesel fuel and permits a range of approx. 250 km per tank fill.

Other components for cooling the fuel cell and the converters for the power electronics are also mounted on the roof. Additional units are provided for supplying auxiliary consumers such as the steering and brake systems and for heating the passenger compartment. Trials of the new drive system under quasi-practical conditions were carried out successfully with the transport authorities in Nuremberg, Erlangen and Fürth from 10/2000 to 4/2001. Linde set up a hydrogen filling station at the operator's facilities. The bus covered a total of approx. 8,000 km.

Both passengers and bus operator employees were highly interested in this new technology due to the very comfortable propulsion. The noise level inside and outside the bus was also perceived by the passengers as being very low.

5 Experiences during design and integration of the Siemens FC system

Just like the first automobiles, FC buses have not yet reached a common design. The handful of prototypes worldwide show that owing to a non-existent automotive supplier base there is a wide range of technical solutions.

MAN was in the favourable position of already having developed compressed hydrogen storage and electric drive systems already of a proven quality for other applications.

The storage system relies mainly on series production CNG technology with special tests and releases of the safety authorities. Integration and operation of this system has been proved to be free of fault.
The electric drive system uses motors and converters already developed for diesel-electric, trolleybus and hybrid drives. With minor changes, this technology was operational.

For the FC system test and integration, an original rear-end space frame of the bus was used. It was prepared with all the interfaces and modifications incorporated 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. These tests led to a number of system modifications.
After stable long-time operation under full load at the Siemens facility, the system was signed off by Siemens and MAN for the application.

Integrating the hardware in the bus was almost successful. During the start-up and preliminary testing phase, additional system modifications were carried out. After solving a number of EMC-related problems and bus finishing, the prototype’s “roll out” came after 3 months of intensive integration and testing work.

As mentioned earlier, a lot of components and auxiliaries are industry standard and do not fulfil specific automotive requirements. Reducing costs and increasing reliability for the customer still requires considerable development.

6 MAN's second-generation fuel cell bus

A second low-floor bus with PEM fuel-cell drive is in preparation, fig. 7. This vehicle will have a fuel cell system with an electrical output of 120 kW. This system is being developed by Air Liquide and Nuvera will supply the PEMFC stacks [8]. The project was started in connection with the European THERMIE programme in 1998 and is coordinated by the Senate of Berlin, fig. 8.

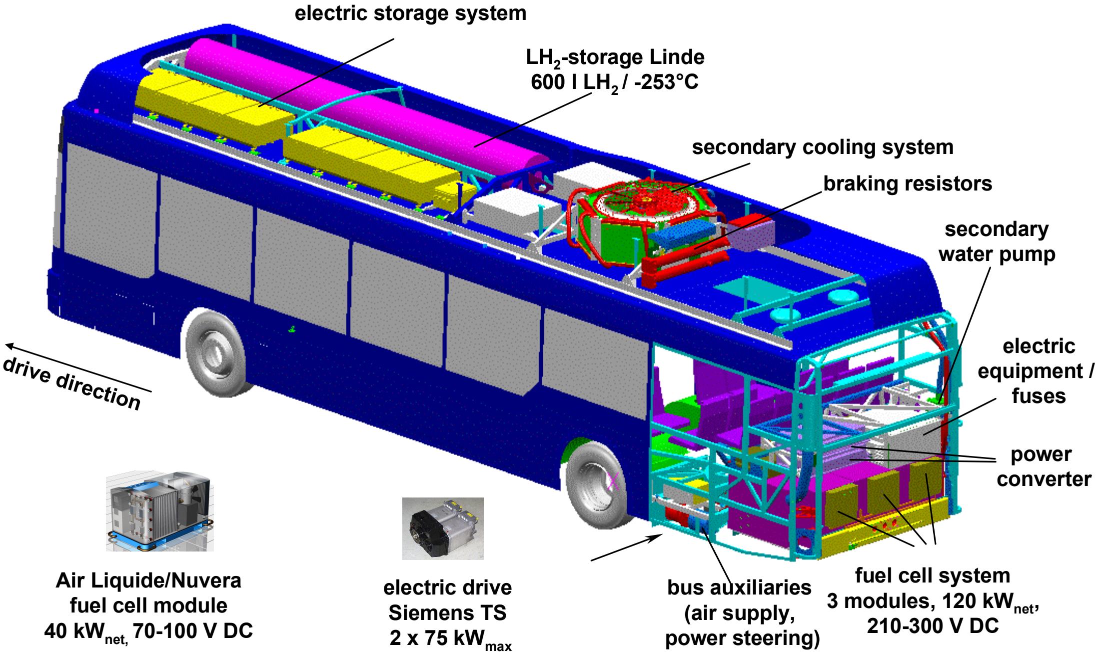

Fig. 7: Concept of the second fuel-cell bus from MAN

The fuel used will be liquid hydrogen. The liquid hydrogen system for the bus will, for same energy content, need less than half the space and weight of the pressurised storage system for gaseous hydrogen at 250 bar. A disadvantage is the higher energy input in the production of liquid hydrogen. Whether gaseous (pressurised) hydrogen or liquid hydrogen is used will depend on the technical conditions prevailing around the vehicle (volume for installation), the infrastructure and customer requirements (operating range).

This vehicle is soon to pass through a nine-month trial operation in Berlin on BVG`s routes. This will commence from the beginning of 2002. After this, short periods of deployment on routes in Lisbon and Copenhagen are planned. In a second phase of the project, an electrical energy storage system will be added to the drive system and there will be a second demonstration phase with the bus operators.

Project coordination	Senate of Berlin
Vehicle	**MAN Nutzfahrzeuge AG, Munich**
Type length, gross weight passenger capacity	**Low floor bus MAN NL 263** 12 m, 18 t; approx. 70 persons;
Propulsion system drive power (max.)	**Central drive unit with e-motors from Siemens TS** 2 x 75 kW, via summation gearbox
Hydrogen storage system tank volume gross weight	**Liquid hydrogen tank from Linde** 600 l LH_2 / -253°C; approx. 800 kg (incl. 50 kg hydrogen)
Fuel cell system Fuel cell stacks power output (net) voltage range system weight	**Air Liquide (France), Air Liquido (Portugal)** 3 stacks from Nuvera (Italy) 120 kW_{net} 190-280 V approx. 800 kg
Bus operation in phase 1 **(12 months)**	**BVG/Berlin** Hydrogen supply, 9 months bus operation in Berlin **Carris (Portugal)** 2 months bus operation in Lisbon **HT (Denmark)** 1 month bus operation in Copenhagen
Simulation FC-bus, telematics	**IST (Portugal)**

Fig. 8 project partners and technical data

7 High-dynamic energy storage systems in supercapacitors

Operation of road vehicles in urban environments is characterised by a large number of acceleration and braking procedures. In contrast to long-haul deployment, noticeable fuel savings can be achieved here by recovering part of the drive energy expended and by operating the fuel cell system at good efficiencies. During coasting, electrically driven vehicles produce electricity like a generator and this energy can be used for the next moving-off procedure.

MAN has examined a variety of solutions using mechanical and electrical storage concepts. In the past, high hopes have been placed in battery concepts, but it has proved that these are not very suitable because their power and energy density is too low for single-mode or hybrid commercial-vehicle drive systems. One concept for high-dynamic storage makes use of the charge storage in so-called supercapacitors.

Together with Siemens/EPCOS MAN has commenced development of high-power capacitors that are to be used initially in city buses. A first prototype system was installed in a diesel-electric city bus.

The actual energy recovery depends to a large extent on the deployment profile around town. In normal city traffic, as often encountered by road vehicles for public transport, energy recovery can reduce consumption by up to 15 %. Operation in bus lanes permits controlled braking with maximum energy recovery, thus resulting in even larger reductions in fuel consumption.
Apart from the saving in energy consumption, capacitors can have a favourable effect on driving dynamics. The power needed for moving off can be added from the storage system. The hybrid drive system does not have to be designed to provide the full power for moving off in such cases, and this reduces the costs. MAN will be examining hybridisation in combination with a fuel cell system in a later phase of the project in which the second MAN fuel cell bus will go into service with bus operators.

8 Prospects

From a technological viewpoint, fuel-cell drive systems have now reached an advanced development status and will in the next few years have no drawbacks with regard to their size and installation space compared to conventional engines. Market acceptance will depend not only on the infrastructure but also on when these drive systems reach a cost level that is acceptable to the market.

In the case of commercial vehicles, all alternative drive systems have to be measured against established drives, fig. 9. Before a market launch, the costs must be brought down to the level of natural gas powered city buses.

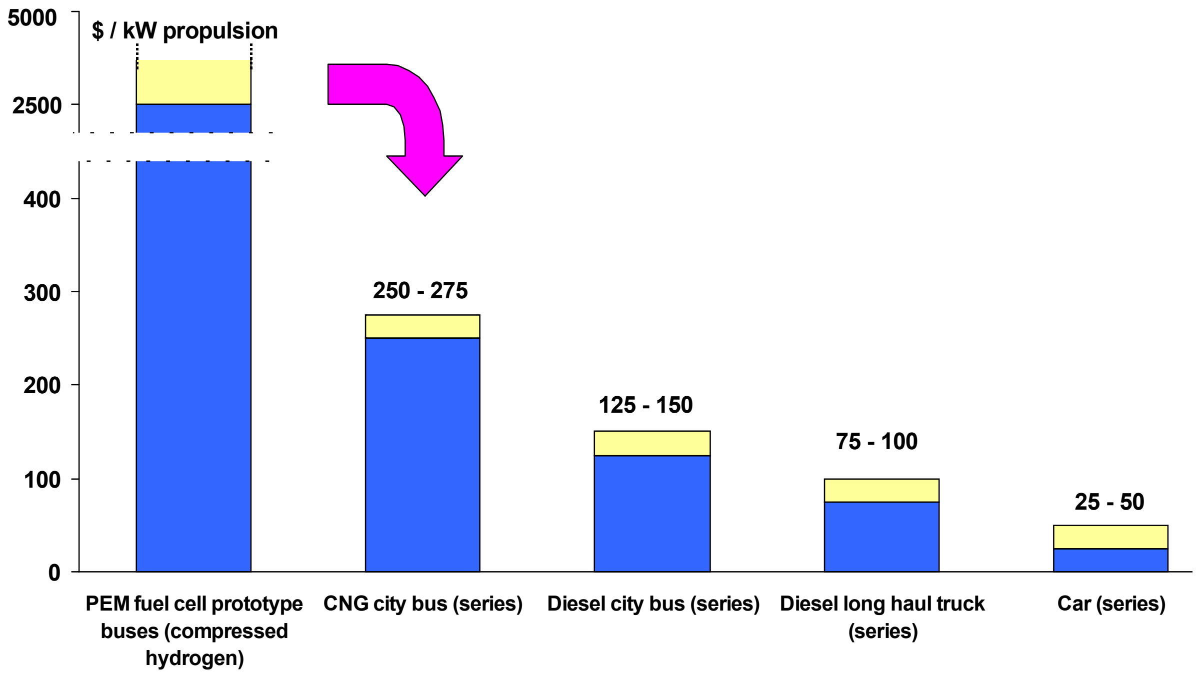

Fig. 9: Target costs of alternative drives including fuel storage systems for commercial vehicles

Trials of fuel cell hydrogen buses in local public transport will secure the acceptance of the new fuel and drive system among operators and passengers and will play an important role in preparations for the market launch. The essential pre-condition for series production is further technological developments in fuel cells, hydrogen storage systems and electrical drive systems. Only in this way can the requirements for a broad-based introduction be satisfied, in particular those relating to costs.

Energy storage systems with a high cost reduction potential such as supercapacitors reduce energy consumption and will have a positive impact on operating costs.

MAN will continue its engagement in alternative drive development. In the next two years, two further fuel cell buses are planned in the context of phase two of the Bavarian Hydrogen Project at Munich Airport. The supplier for the stacks could be International Fuel Cells from UTC.

MAN regards eight to ten years as a realistic period before series production of city buses with fuel-cell drive can begin.

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