Available online at www.sciencedirect.com
SCIENCE DIRECT®
Journal of Power Sources 118 (2003) 349–357
JOURNAL OF POWER SOURCES
www.elsevier.com/locate/jpowsour

Real life testing of a Hybrid PEM Fuel Cell Bus

Anders Folkesson[a,*], Christian Andersson[b], Per Alvfors[a], Mats Alaküla[b], Lars Overgaard[c]

[a]Energy Processes, Department of Chemical Engineering and Technology, Royal Institute of Technology, Teknikringen 50, SE-10044 Stockholm, Sweden
[b]Department of Industrial Electrical Engineering and Automation, Lund University, Lund, Sweden
[c]Bus Chassis Pre-Development Department, Scania, Sweden

Abstract

Fuel cells produce low quantities of local emissions, if any, and are therefore one of the most promising alternatives to internal combustion engines as the main power source in future vehicles. It is likely that urban buses will be among the first commercial applications for fuel cells in vehicles. This is due to the fact that urban buses are highly visible for the public, they contribute significantly to air pollution in urban areas, they have small limitations in weight and volume and fuelling is handled via a centralised infrastructure.

Results and experiences from real life measurements of energy flows in a Scania Hybrid PEM Fuel Cell Concept Bus are presented in this paper. The tests consist of measurements during several standard duty cycles. The efficiency of the fuel cell system and of the complete vehicle are presented and discussed. The net efficiency of the fuel cell system was approximately 40% and the fuel consumption of the concept bus is between 42 and 48% lower compared to a standard Scania bus. Energy recovery by regenerative braking saves up 28% energy. Bus subsystems such as the pneumatic system for door opening, suspension and brakes, the hydraulic power steering, the 24 V grid, the water pump and the cooling fans consume approximately 7% of the energy in the fuel input or 17% of the net power output from the fuel cell system.

The bus was built by a number of companies in a project partly financed by the European Commission's Joule programme. The comprehensive testing is partly financed by the Swedish programme ''Den Gröna Bilen'' (The Green Car). A 50 kW_{el} fuel cell system is the power source and a high voltage battery pack works as an energy buffer and power booster. The fuel, compressed hydrogen, is stored in two high-pressure stainless steel vessels mounted on the roof of the bus. The bus has a series hybrid electric driveline with wheel hub motors with a maximum power of 100 kW.

Hybrid Fuel Cell Buses have a big potential, but there are still many issues to consider prior to full-scale commercialisation of the technology. These are related to durability, lifetime, costs, vehicle and system optimisation and subsystem design. A very important factor is to implement an automotive design policy in the design and construction of all components, both in the propulsion system as well as in the subsystems.

Keywords: PEM fuel cell system; Hybrid bus; Test; Hydrogen

1. Introduction

Even though only a small percentage of all vehicles in the world are urban buses, they impact disproportionately on public health. The reason for this is that they are concentrated to urban areas. The most important emissions from ordinary city transit buses with Compression Ignition (CI, i.e. Diesel) engines are particulates and nitrogen oxides (NO_x). Particles especially are believed to cause severe health problems and are possibly carcinogenic. Nitrogen oxides are important components in the formation of smog, contribute to acid rain, the eutrofication of lakes and seas and cause health problems.

Urban buses are, for several reasons, one of the best applications for commercialisation and testing of new, alternative fuels and advanced propulsion technologies:

1. They operate in urban areas where air pollution is considered a problem.
2. They are usually co-ordinated and fuelled centrally.
3. They are highly visible for the public.
4. They are often subsidised by government funds.
5. There is space available for the fuel cell system (both in volume and weight).

Fuel cell technology enables Zero or Ultra Low Emission Vehicles (ZEV or ULEV) with increased comfort due to very low noise levels and the possibility to use fully electric, stepless, drivelines. Fuel cells systems have high efficiencies, especially at part loads and have the potential for further

* Corresponding author. Tel.: +46-8-7906531; fax: +46-8-7230858.
E-mail address: anders.folkesson@ket.kth.se (A. Folkesson).

0378-7753/03/$ – see front matter
doi:10.1016/S0378-7753(03)00086-7

development in building simple systems with long lifetime due to very few moving parts. Drawbacks with the fuel cell technology today are high costs, limited lifetime and the need of a new fuel infrastructure.

There are other types of environmentally friendly bus concepts. For example, busses with conventional Internal Combustion Engines (ICEs) fuelled with different kinds of alternative fuels, such as ethanol, methanol, Liquefied Petroleum Gas (LPG), Compressed Natural Gas (CNG), biogas, improved diesel, synthetic diesel or hydrogen. Different ICE/Electric hybrid configurations are also possible. Comparisons, evaluations and modelling studies of different alternative propulsion technologies can be found in the literature [1–9]. Studies of fuel cell systems and fuel cell electric hybrid propulsion systems for automotive applications have also been published [10–12]. New ICE technologies as Homogenous Charge Compression Ignition (HCCI) engines are under development as well as different ICE-based hybrid electric configurations. All those techniques have environmental benefits compared to conventional IC engines running on regular diesel or petrol, and are good environmentally friendly alternatives in the short perspective. However, given the limited resources of fossil fuels, fuel cells are, from a long-term perspective, a very competitive alternative for powering environmentally friendly vehicles, at least in urban areas. For long range heavy transports will the constantly improving CI-engine technology remain the best alternative for the foreseeable future. Fuel cells might be relevant for non-propulsion purposes such as cabin heating and electricity supply.

Several Fuel Cell Bus prototypes have been presented during the last decade and more are to come. However, there is very little information published about fuel cell vehicle testing, concerning both cars and buses [13–15]. Some new projects like the Clean Urban Transport for Europe (CUTE) project, now targets not only the evaluation of the vehicle technology but also the question of the necessary infrastructure [16].

2. Background/Hybrid Fuel Cell Concept Bus project

The objective of the Hybrid Fuel Cell Concept Bus project was to design and build a demonstration vehicle in the shape of a hybrid Fuel Cell Bus. The project was supported by funds from EU's Non-nuclear energy (Joule) programme. Several companies and institutes were involved as partners or participants in the project:

- Air Liquide (France)
  Project management.
  Fuel cell module (FCM) design and construction.
  Hydrogen storage system design and construction.
- SCANIA (Denmark/Sweden)
  Bus construction.
  Battery supply and construction.
  SCANIA has ZF (Germany) as electric driveline supplier.
- SAR (Germany)
  Power bus controller and dc/dc electrical converter design.
- Nuvera Fuel Cells Europe (Italy)
  Fuel cell design and construction.
- Universita di Genova (Italy)
  Air compressor module design.
  Compressor from Opcon Autorotor (Sweden).
- Commissariat à l'Energie Atomique (France)
  Fuel cell tests.

The project started in 1996 and SCANIA was involved from 1999. The project was originally to be closed by the end of year 2000, but due to technical problems it was delayed to the summer of 2001. The concept bus study continues within a project supported by the Swedish National Research Programme for Green Car Research and Development (Sweden: Den Gröna Bilen). The aim of this project is to gather knowledge and experience in using fuel cells and hybrid technology in heavy vehicles. The project involves SCANIA, The Royal Institute of Technology—KTH (Stockholm) and Lund University of Technology—LTH (Lund). Results from the first part of that project; Testing of the Hybrid Fuel Cell Concept Bus is presented in this paper. Test results obtained in this part will be used in part two of the project, in simulation studies of future bus concepts.

3. The bus

The bus type is a construction from the 1990s for inner city and airport traffic, called SCANIA Service Bus. The bus is 9.2 m long, 2.5 m wide and 3.2 m high and has capacity for 15 seated and 37 standing passengers (Table 1). It is a true low floor bus, which means that the passenger compartment has a completely flat and low floor.

A diesel–electric hybrid bus, developed by SCANIA and the German company ZF in the 1990s, is partly used as base for the Fuel Cell Bus (Fig. 1), but it has been fundamentally reconstructed for the new fuel cell and hydrogen technology.

Fig. 1. The SCANIA Hybrid Fuel Cell Concept Bus.

Table 1
General technical description of the bus and the propulsion system

Bus type: SCANIA Service Bus	Description
Technical	
Dimension ($L \times W \times H$)	9.2 m × 2.5 m × 3.2 m
Max weight	13 t
Passenger capacity	52
Propulsion system type	Series hybrid with regenerative braking
Fuel cell system	
PEM FC stacks (×2)	2 × 105 cells
Power output (gross)	0–50 kW
Cooling	Water
Hydrogen storage	
Material	Stainless steel
Maximum pressure	200 bar
Capacity	13.2 kg H_2
Driveline battery	
Lead acid VR	44 × 12 V
Nominal voltage	528 V
Energy density	35 Wh/kg
Power density	380 W/kg
Cooling	Air
Driveline	
Motors (×2)	Wheel hub
Power output	2 × 50 kW
Cooling	Water

The bus is equipped with a series hybrid driveline (Fig. 2), which means that the driveline is completely electric and uses energy that is supplied from more than one source.

In this configuration, the driveline receives energy from both the fuel cell system and a battery. As the battery serves as a high power energy reservoir, it enables the use of a rather small, and therefore less expensive, fuel cell system.

The fuel cell system has a designed maximum power output of 50 kW. The fuel is compressed hydrogen and the oxygen for the fuel cell is compressed ambient air. An integrated dc/dc converter adjusts the fuel cell output voltage with the voltage of the common power bus (600 V).

The propulsion system is located in the rear end of the bus (see Figs. 1 and 3). The whole system, including the fuel cell system, battery, wheel motors and power electronics and auxiliaries can easily be removed from the rest of the bus. This simplifies service and other work on the system.

The propulsion system consists of

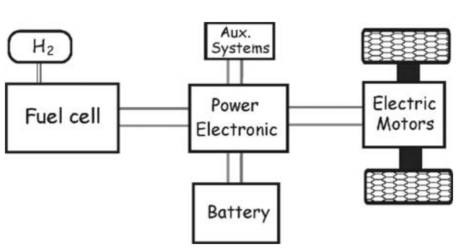

Fig. 2. A series hybrid system.

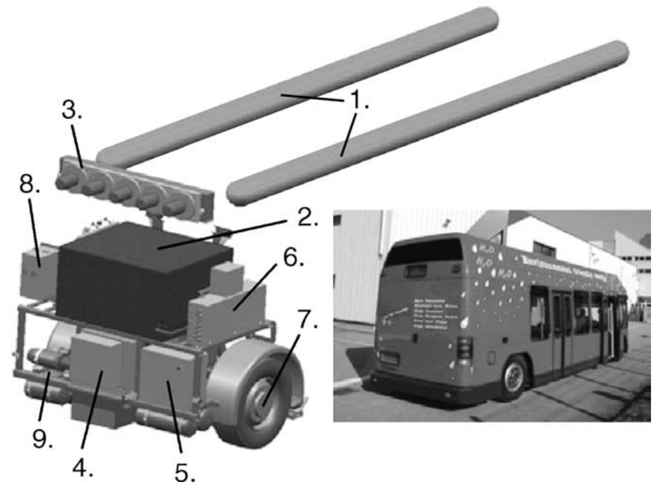

Fig. 3. The propulsion system located in the rear of the rear end of the bus.

(1) 200 bar hydrogen storage vessels;
(2) fuel cell system;
(3) radiator and fans for the secondary cooling system;
(4) high voltage battery module;
(5) power electronics;
(6) inverter and control system for wheel hub motors;
(7) wheel hub motors;
(8) auxiliary inverters; and
(9) auxiliary systems: air compressor and hydraulic system.

3.1. The fuel cell system design

In a fuel cell, the chemical energy in a fuel (i.e. hydrogen) is directly, without combustion, converted to electricity in an electrochemical reaction. If hydrogen is stored onboard a vehicle, the only local emission from the vehicle will be water. The fundamentals of fuel cells can be found in several previous published publications [17,18].

The fuel cell system (Fig. 4) consists of fuel cell stacks, a hydrogen circuit, an air circuit, a primary and a secondary

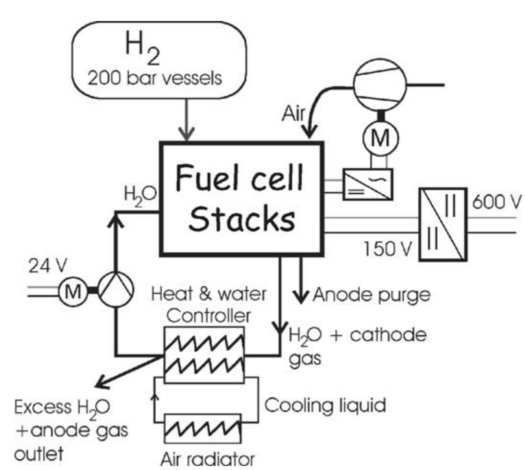

Fig. 4. The fuel cell system.

cooling water loop. The output voltage is harmonised with the high voltage system in the bus via a dc/dc converter.

The heart of the fuel cell system is the stack module with two PEM fuel cell stacks. Each stack contains 105 cells. The stack module has a maximum power output of 50 kW in the SCANIA Fuel Cell Bus configuration. The stack supplier is the Italian company 'Nuvera Fuel Cells Europe' and the two stacks were integrated into a complete fuel cell module designed and constructed by the French company 'Air Liquide'.

The stacks assembly components are metallic. Its dimensions are 58 cm height, 42 cm width and 57 cm length, giving a total volume of 139 l. This results in a power density of approximately 0.2 kW/l. It has to be noted that the stack design is from 1997/1998 if compared with today's state of the art stacks where power densities of >1.5 kW/l have been demonstrated [19,20]. The new generations of stacks that Nuvera works with today have an improved performance, with power densities of over 1 kW/l. With power densities of >1 kW/l, the stack size and weight is not a key problem in bus applications. More critical problems are the size and weight of the auxiliary systems, the fuel storage systems and the batteries.

Excess heat has to be removed from the fuel cell system in order to keep the temperature in the fuel cell stacks within the desired temperature interval. A lot of heat is transferred to the surroundings with the exhaust gases but the rest has to be cooled away. In the design tested, pure water is directly injected to the stack. This, the primary cooling circuit is heat-exchanged with a secondary cooling circuit, integrated with the heating system for the bus cabin. The secondary cooling systems are connected to a fan assisted radiator system, located on the roof of the bus. Some heat is also removed through a ventilation system that ventilates the fuel cell/engine section of the bus and via heat radiation.

A water management system is integrated with the thermal management system. There is no system for pre-humidification of the reactant gases. This reduces the cost, complexity, and size of the whole system. Instead of pre-humidification, the pure cooling water is directly injected into the stack where it both humidifies the membrane and controls the temperature of the stack, i.e. cools it down.

The outgoing airflow from the stack contains great amounts of water. In order to keep the global water balance, some of that water is collected in an exhaust gas condenser.

Air (i.e. oxygen) is supplied to the fuel cell via a twin-screw, oil-free, compressor. An air filter and silencer system is mounted prior to the compressor. The compressor motor is direct-powered by one of the fuel cell stacks, without conversion via the main dc/dc converter, but via conversion to ac electric power in a separate inverter for the compressor motor.

The fuel, hydrogen, is stored as compressed gas in two 200 bar stainless steel pressure vessels, located on the roof of the bus. The total amount of stored hydrogen gas is 875 l or 13.2 kg. The pressure is lowered in two stages before the gas enters the stacks. It is first lowered to <10 bar on the roof, then transferred to the fuel cell where the pressure is lowered to the working pressure of the stacks.

4. Testing and test results

The performance of the bus has been tested thoroughly at IDIADA in northern Spain [21]. IDIADA is a commercial proving ground that vehicle producers from all over the world use for different kinds of vehicle testing. The facilities include:

1. high-speed circuit;
2. external noise test track;
3. dynamic platforms;
4. handling track;
5. general road circuit;
6. accelerated fatigue track;
7. test hills;
8. straight line braking surfaces;
9. comfort track;
10. customer workshops.

All tests were performed with the bus loaded with external weights so that the total weight was $12,500 \pm 25$ kg.

4.1. Data acquisition equipment

The data acquisition system used in the bus comes from IPETRONIK and is called SIM. The system is compact, with different kinds of modules for different sensor types. All the modules have in-built power supply (0–60 V) for the sensors. This makes the system suitable for automotive applications.

Software from National Instruments, called DIAdem, is installed on the notebook and used to control the data acquisition and to store the data on disc. This measurement data becomes available for further processing in Matlab. The programming in DIAdem is graphically similar to LabVIEW. An overview of the measuring system layout is shown in Fig. 5.

4.2. Aerodynamics and roll-resistance

To test the aerodynamics and roll-resistance of the bus, a roll-out test was done. The bus was accelerated to a certain speed, in wind-free conditions, and then allowed to roll on a flat road until it stopped. At a roll-out test from 60 km/h, the bus rolled 1300 m.

4.3. Acceleration

The acceleration performance of a bus is an important factor since it must be able to follow the traffic pace in a city. Acceleration tests were performed on a flat road in wind-free conditions and the acceleration performance is plotted in Fig. 6. The bus reaches 30 km/h in 7 s and 60 km/h in 25 s.

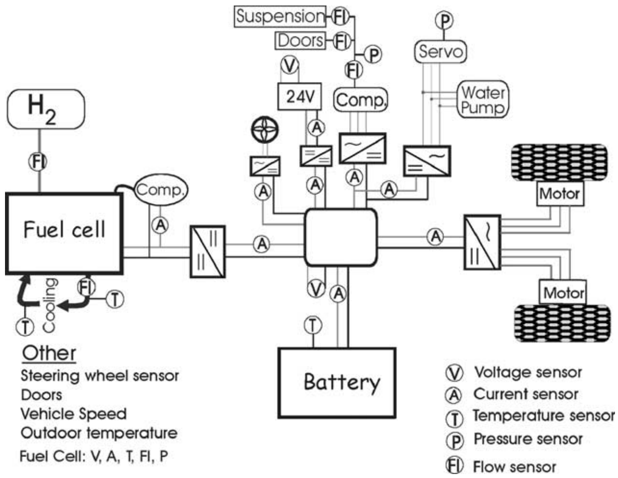

Fig. 5. Measuring system layout showing all important sensors and subsystems.

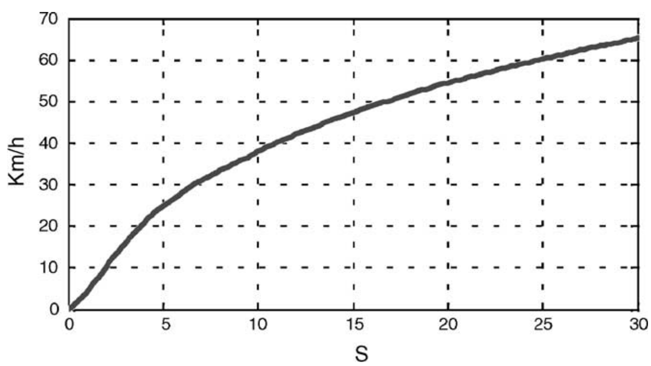

Fig. 6. Acceleration performance.

4.4. Hill climbing

The hill climbing capability of a bus is important in hilly cities, if the bus shall manage to drive certain routes. This requests a minimum of toque of the electric drive motors. The bus managed to climb an 18% steep hill for 75 m and a long 12% steep hill without problems.

4.5. Duty cycles

The bus was tested in accordance to several standardised duty cycles in order to evaluate the performance of the bus. Two duty cycles are discussed in this paper; the Braunschweig city duty cycle and the FTP 75 duty cycle. The Braunschweig city duty cycle is a recorded urban cycle, with high accelerations and many stops. It represents a typical driving pattern for a bus or a distribution truck travelling in urban areas. The duty cycle is used by MTC AB, a subsidiary of the Swedish Motor Vehicle Inspection Company (ASB) for testing of buses and distribution trucks. FTP 72 is also a recorded cycle. It is an American cycle from the beginning of the 1970s. The full version is called FTP 75, which is the FTP 72 cycle extended with 500 s. The bus was also tested in accordance with other cycles, such as artificially made duty cycle ECE 15. Those test results are not presented in this paper, due to the fact that they do not represent real city driving as FTP and Braunschweig do.

The bus ability to follow the standardised duty cycles is satisfactory. A comparison of the reference speed and the actual speed is shown for the Braunschweig and the FTP 75 duty cycles in Figs. 7 and 8.

A segment (55 s) showing a single acceleration and retardation in the Braunschweig cycle is shown in Fig. 9. The power from/to the electric drive motors are shown in the same figure. When the bus accelerates, the electric motors consume the power that the battery and the fuel cell supplies. Consequently, when the bus brakes the electric motors start to generate power, which is used to charge the battery. The efficiency of the regenerative system, i.e. the storage of energy into the battery during braking and the utilisation of energy from the battery during acceleration, was typically 85% in the tests.

The maximum total power from the battery and the fuel cell system is approximately 135 and >40 kW (net), respectively and the maximum power to the driveline motors during acceleration and from the driveline motors during regenerative braking are 130 and 100 kW, respectively.

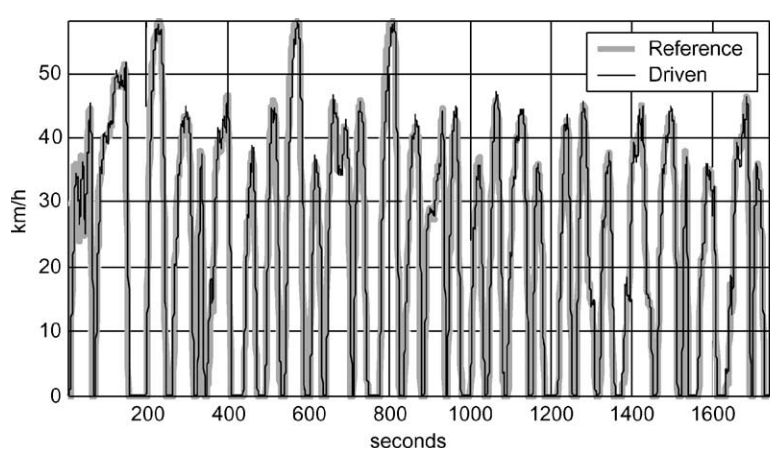

Fig. 7. The Braunschweig duty cycle. Presentation of reference speed and actual (driven) speed.

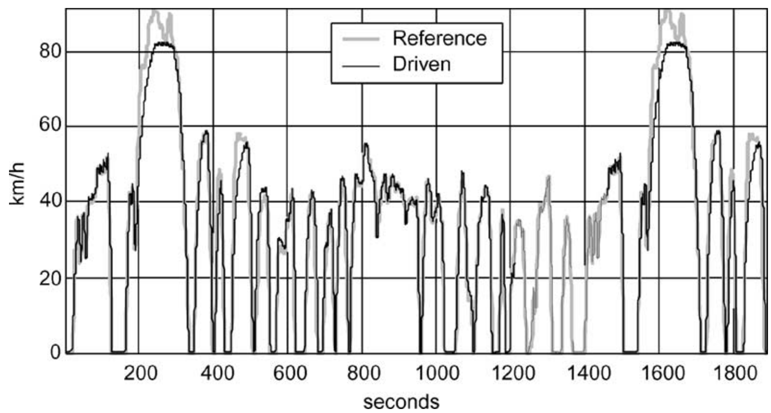

Fig. 8. The FTP 75 duty cycle. Presentation of reference speed and actual (driven) speed. Note that the maximum speed is electronically limited to 80 km/h.

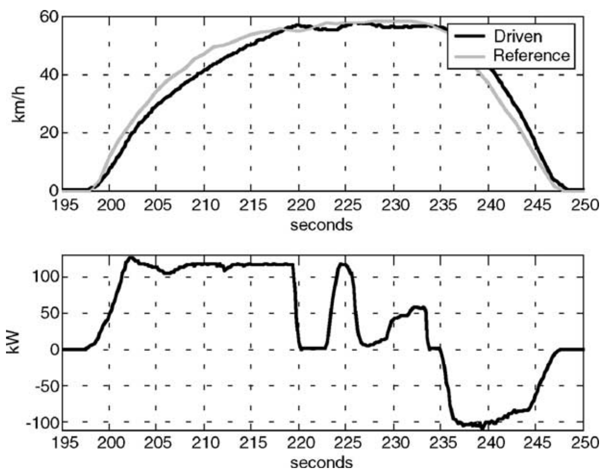

Fig. 9. Actual (driven) and reference speed and power from/to the electric motors for a segment of the Braunschweig duty cycle.

A comparison of the energy consumption for the Fuel Cell Bus at the two duty cycles and a standard SCANIA Omni City bus with a CI-engine is shown in Fig. 10. Energy consumption values are converted to diesel equivalents per 100 km. The energy consumption is between 42 and 48% lower for the Fuel Cell Bus than for the conventional bus. The figure clearly shows the advantages with a hybrid vehicle, in which the regenerated energy can be stored in a battery. The regeneration extends the range of the bus with 24–28% in these city duty cycles. Also, without the regenerative braking the bus would have been 21–32% more efficient than the standard bus.

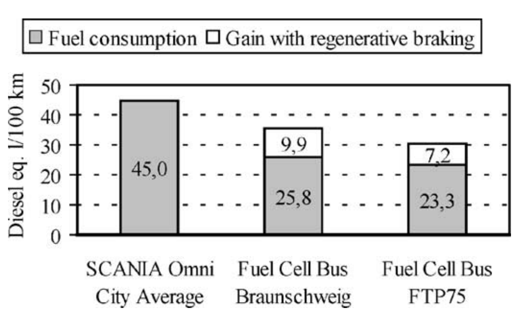

Fig. 10. The energy consumption of the Fuel Cell Bus, as diesel equivalents for the Braunschweig and FTP 75 duty cycles, in comparison with a SCANIA standard Omni City bus.

4.6. Subsystems

The energy consumption of different subsystems in the bus was measured in order to map the energy flow in the bus and to find optimisation potentials. The subsystem consumes approximately 7% of the total energy input. The mean power consumption for the subsystems is 3–4 kW depending on the duty cycle, which is approximately 7% of the lower heating value of the consumed hydrogen. This includes ordinary bus stops (door openings and vertical adjustment of bus) at city driving but no air condition system. An air condition system for a 9 m bus, consumes up to 15 kW [13].

4.7. Fuel cell tests

The fuel cell module was specifically tested at the Air Liquide facility in Sassenage in France. Due to technical problems during the final fuel cell test, detailed test results are only presented up to 13 kW gross output power. Nominal power was achieved and tested at an earlier stage, hydrogen fuel consumption was not measured at that time, though. Results are presented for the tests and a prediction is made for higher loads in Fig. 11.

The temperature level in the stack during the tests was in the 50–75 °C range. The pressure on the air side was approximately 1.3 bars and on the hydrogen side approximately 1.5 bars. The stoichiometric factor (excess air factor) was approximately 1.5 during normal operation and as high as 4 at very low power output. The voltage and current levels of the systems are 145–180 V and 0–350 A, respectively.

4.8. Energy flow visualisation

It is interesting to study the different energy flows within the bus. In Fig. 12, the time average power flows during the

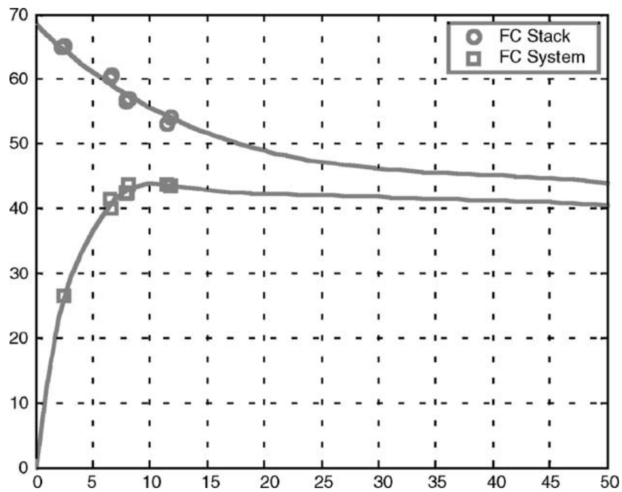

Fig. 11. The efficiency of the fuel cell stacks and the fuel cell system as a function of load. Rings and squares mark measured values and the lines predicted values.

Braunschweig cycle is shown. It is important to stress that the figure represents average values and that the situation shown in the diagram does not correspond to an actual situation.

4.9. Noise tests

External noise emissions of the bus were measured at IDIADA. The test was performed as an accelerated passage test, defined by the European regulation 70/157/EEC. In the test, the bus is accelerated to a speed of 50 km/h, which is held constant when it approaches the measuring area. As it enters, a full acceleration is performed during a 20 m long test (measuring) strip while the noise is measured at a specified distance on both side of the bus. The noise level

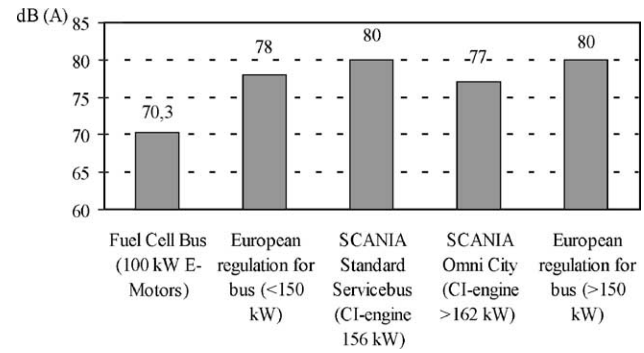

Fig. 13. Results from noise measurements, defined by the European regulation 70/157/EEC.

is compared with the same bus type, but with its standard engine and driveline configuration in Fig. 13. A comparison is also made with the present noise regulations. There is a breakpoint in the regulations for buses at 150 kW but it is not clear, though, which noise level the Hybrid Fuel Cell Bus shall be compared with. This is due to the fact that power sources together deliver more than 150 kW, but the driveline only consumes a maximum of 130 kW.

5. Experiences and conclusions

Hybrid Fuel Cell Buses have a big potential, not only with their high efficiencies and ZEV potential, they also offer other values such as very low noise levels and high comfort levels.

Regenerative braking gives a higher efficiency. Gains of between 24 and 28% can be made in urban duty cycles with many "stop and go" situations. The gain with a regenerative braking system is also achieved in ICE hybrid electric driveline systems.

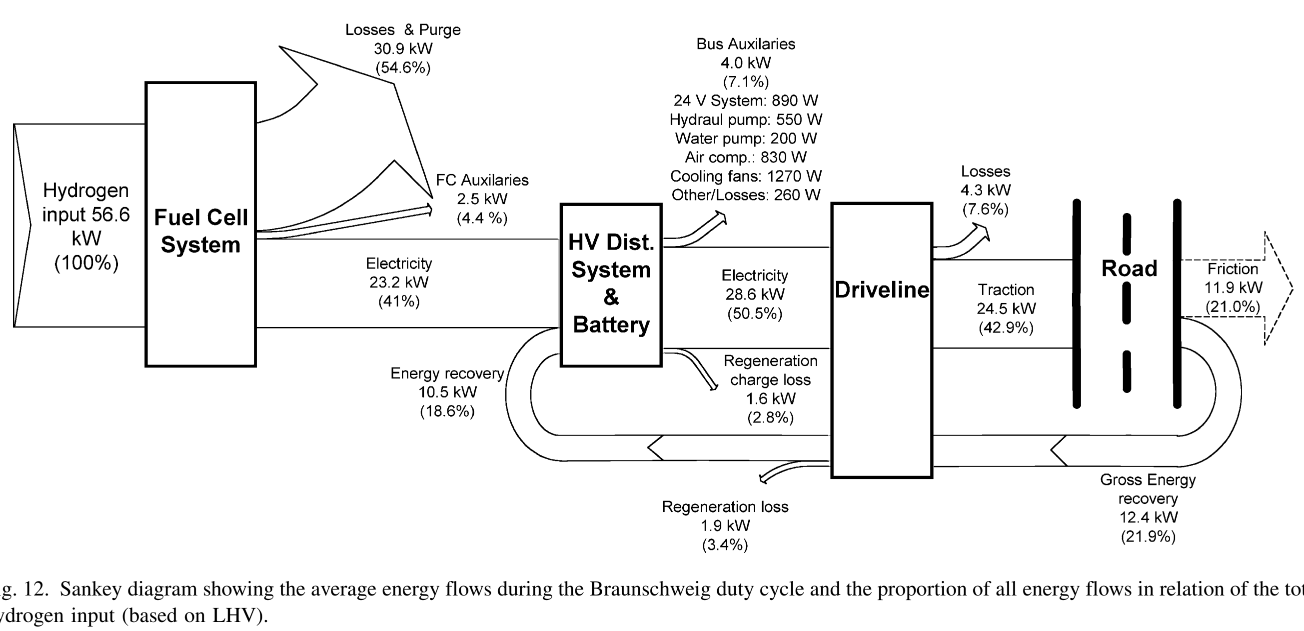

Fig. 12. Sankey diagram showing the average energy flows during the Braunschweig duty cycle and the proportion of all energy flows in relation of the total hydrogen input (based on LHV).

The mean power consumption for the 12.5 t concept bus is approximately 17–24 kW during the tested duty cycles. This means that a fuel cell system with a nominal power output of approximately 35–50 kW would be enough for a full size (12 m) hybrid electric city bus, even with a 20–25 kW air condition system installed. The energy buffer and power booster system, consisting of batteries, supercapacitors, or a mix of both, will then handle power peaks.

Many of the installations in the Fuel Cell Concept Bus are not optimised for automotive use concerning weight, size and lifetime. Nor is the bus designed for gaseous fuels from the beginning. Consequently, there is an optimisation potential in the general bus concept design. Electric drivelines in general enable completely new vehicle designs, with no limitations imposed by large mechanical transmission systems.

6. Future work

Several tasks or problems with the fuel cell technology and hybrid electric drivelines have to be solved prior to a mass-introduction of fuel cells on the vehicle market in general and on the urban bus market in particular.

6.1. Durability and lifetime

All propulsion system components as well as all subsystem components must be designed following automotive design rules for heavy-duty vehicles. The lifetime must be improved, in particular for the fuel cell stacks.

6.2. Cost reduction

Cost reduction can be achieved by lowering the complexity of the fuel cell system and by implementing industrial standards and better manufacturing methods. Development of new materials or a different choice of materials is also an important matter of concern. For instance, the noble metals that are used as catalyst in the fuel cells stacks and in fuel reformer systems are both a limited resource and expensive. Also the cost for other components in the propulsion system must be reduced. For example, driveline components such as power electronics and motors, or energy buffer systems such as batteries or supercapacitors. The cost of a new fuel infrastructure is also an important issue.

6.3. Fuel storage systems

Safe, light, energy efficient and inexpensive fuel storage systems for onboard storage of hydrogen must be developed.

6.4. Cooling system

A problem with this generation of PEM fuel cells is the relatively low working temperature of the stacks (70–85 °C). This demands large cooling systems due to the low temperature difference between the warm medium and the surroundings. The temperature difference is the driving force in the heat exchange process and a low difference requires a high flow of the cooling media and/or large heat exchanger surfaces. Another problem is that the cooling liquid will have a temperature that is too low for use in heating systems designed for CI-engines even though the amount of heat energy available is enough. This in turn leads to special and expensive systems only suitable for fuel cell powered vehicles. The temperature of the fuel cell systems have to increase to match or at least be closer to the temperature in CI-engine cooling systems.

6.5. Voltage

Higher voltage and consequently lower currents in the fuel cell system will lead to an easier handling of the power conversion and therefore lower cost, volume and weight of the power conversion system.

6.6. Optimisation

The specification of the vehicle, i.e. the relation in capacity of the primary energy source (fuel cell) contra the energy buffer (battery, supercapacitors) must be optimised. It is also necessary to design the whole vehicle for gaseous fuels from the beginning.

6.7. Subsystems

All subsystems that are not electrical today must be replaced by similar optimised electrical subsystems.

Acknowledgements

This work was financed by VINNOVA (Swedish Agency for Innovation Systems) and SCANIA.

References

[1] P. Mizsey, Comparison of different vehicle power trains, J. Power Sources 102 (2001) 205–209.

[2] F. Kreith, R.E. West, B.E. Isler, Efficiency of advanced ground transportation technologies, J. Energy Res. Technol. 124 (2002) 173–179.

[3] L. Lave, H. MacLean, C. Hendrickson, R. Lankey, Life-cycle analysis of alternative automobile fuel/propulsion technologies, Environ. Sci. Technol. 34 (17) (2000) 3598–3605.

[4] K. Jonasson, P. Strandh, M. Alaküla, Comparative study of generic hybrid topologies, in: Proceedings of the 18th International Electric Vehicle Symposium, Berlin, Germany, October 20–24, 2001.

[5] G. Rizzoni, L. Guzzella, B.M. Baumann, Unified modeling of hybrid electric vehicle drivetrains, IEEE/ASME Trans. Mechatron. 4 (3) (1999) 246–257.

[6] A.K. Shukla, A.S. Aricò, V. Antonucci, An appraisal of electric automobile power sources, Renew. Sustain. Energy Rev. 5 (2001) 137–155.

[7] L.U. Gökdere, K. Benlyazid, R.A. Dougal, E. Santi, C.W. Brice, A virtual prototype for a hybrid electric vehicle, Mechatronics 12 (2002) 575–593.
[8] P. Van den Bossche, Power sources for hybrid buses: comparative evaluation of the state of the art, J. Power Sources 80 (1999) 213–216.
[9] A.F. Burke, M. Miller, Fuel efficiency comparisons of advanced transit buses using fuel cell and engine hybrid electric drivelines, in: Proceedings of the 35th Intersociety Energy Conversion Engineering Conference, Las Vegas, NA, USA, July 24–28, 2000, vol. 2, 2000, pp. 1333–1340.
[10] H.-G. Jeong, B.-M. Jung, S.-B. Han, S. Park, S.-H. Choi, Modeling and performance simulation of power systems in fuel cell vehicle, in: Proceedings of the Third International Power Electronics and Motion Control Conference, Beijing, China, August 15–18, 2000, vol. 2, 2000, pp. 671–675.
[11] S.G. Chalk, J.F. Miller, F.W. Wagner, Challenges for fuel cells in transportation applications, J. Power Sources 86 (2000) 40–51.
[12] K.S. Jeong, B.S. Oh, Fuel economy and life-cycle cost analysis of a fuel cell hybrid vehicle, J. Power Sources 105 (2002) 58–65.
[13] R. Wimmer, Fuel cell transit bus testing and development at Georgetown University, in: Proceedings of the 32nd Intersociety Energy Conversion Engineering Conference, Honolulu, HI, USA, July 27 to August 1, 1997, vol. 2, 1997, pp. 825–830.
[14] G. Friedlmeier, J. Friedrich, F. Panik, Test experiences with the DaimlerChrysler fuel cell electric vehicle NECAR 4, Fuel Cells 1 (2) (2001) 92–96.
[15] J.T. Larkins, R.R. Wimmer, Fuel cell powered transit bus demonstration and test program, in: Proceedings of the 1998 Fuel Cell Seminar, Palm Springs, CA, USA, November, 1998, pp. 734–737 (Abstracts).
[16] Fuel Cells Bull. March (42) 2002.
[17] J. Larminie, A. Dicks, Fuel Cell Systems Explained, Wiley, England, 2000.
[18] L. Carrette, K.A. Friedrich, U. Stimming, Fuel cells—fundamentals and applications, Fuel Cells 1 (1) (2001) 5–39.
[19] Ballard Fuel Cell Power Module Mark 900 Series, Brochure, 100-0015-PA, Ballard Power Systems, 2000.
[20] A.P. Meyer, M.E. Gorman, D.M. Flanagan, D.R. Boudreau, Progress in the development of PEM fuel cell engines for transportation, SAE Technical Paper 2001-01-0540, 2001.
[21] http://www.idiada.es.