Miniature Fuel Cell Systems for Consumer Applications

Christopher Hebling and Ulf Groos
Fraunhofer Institute for Solar Energy Systems ISE
Heidenhofstr. 2, 79110 Freiburg, Germany

Abstract

The development of miniaturized fuel cell systems as a supplement or a substitute to rechargeable batteries is relatively recent. This is due to the fact, that the technical challenges of complete device integrated systems are manifold and that the battery technology does not keep pace any more with the growing power demand of modern electronic devices. Mobile computing, communication and imaging products such as 4C-products (camcorders, cell phones, computers, cordless tools) converge more and more and as a result of this, there is an increase in intelligence (computation), connectivity (band width), the promotion of ëalways oní and thus a considerable higher power demand. Fuel cells have some significant intrinsic advantages which make them attractive candidates as a power source for future generation products.

Introduction

After some disillusion for fuel cell systems in automotive and stationary applications, portable fuel cell applications are now being faced with extremely high expectations which result from the increasing number of portable electronic applications in general and with their increase in power consumption. This can also be seen on the background of cost since the energy delivered by batteries is the most expensive energy at all (Fig.1). It seems as if niche applications with very special boundary conditions, like for example, remote stationary systems (sensors, long term data acquisition, signalling systems), medical appliances, security cameras, backup power, military systems etc. will the first products which are powered alternatively by fuel cell systems.

Fuel cells can be customised exactly according to the power demand of the respective electronic device and the geometrical design. A fuel cell system can be thought of as an engine (free choice of power) and an fuel reservoir (free choice of capacity). This means that both the total power output of the fuel cell and the energy capacity can be tailored exactly to the requirements of the various electronic devices and the operation time aimed at. This is different with batteries where the capacity is an integral part of the power source.

However, many aspects such as technical challenges, cost and safety issues as well as the need for a different use and maintenance required by the customer as compared to batteries should be addressed (1) (2).

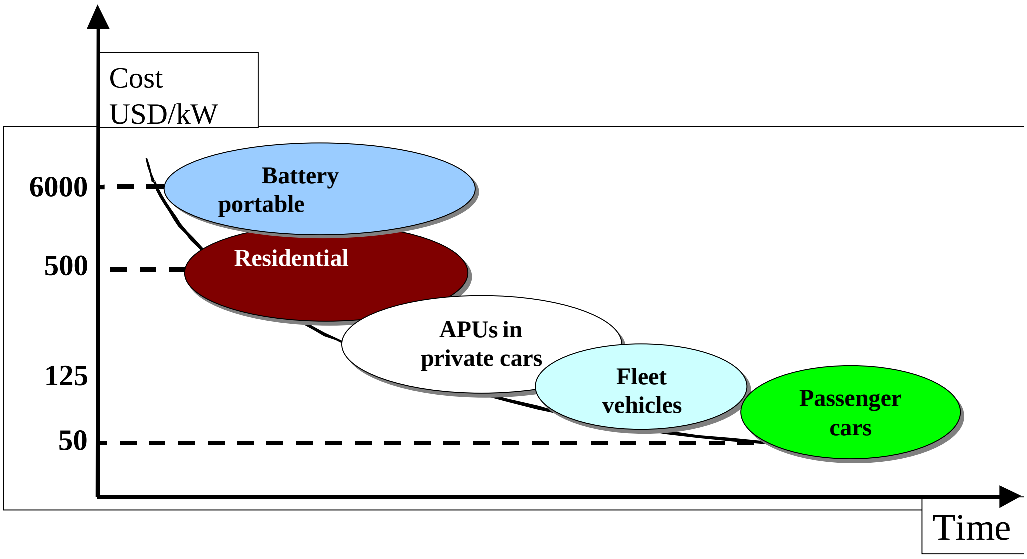

Fig.1 Commercially competitive system costs of fuel cells in the various areas. Qualitative development of the market introduction as it is discussed nowadays.

Technology of small fuel cells

The striking feature of small fuel cell systems is their inherent potential of higher energy densities compared to secondary batteries. This enables the customer to use the respective device much longer without recharging assuming the same weight and volume. Furthermore, due to the independence of the fuel cell and the fuel container, the amount of energy can be tailored to a given application thus opening up an enormous variety of use. In this context, the geometrical adaptability of the fuel cell shape to the given cavities of the various devices is another important benefit compared to batteries.

On the technical side, the most important tasks are the increase of the power and energy density while maintaining the reliability equivalent to the reliability of batteries. Fuel cells usually operate under ambient conditions. Reliable operation and simple system architecture are the contradictory requirements for these applications. Thus, to fulfil these requirements, the main challenges of present and future R&D are to realise a passive thermal and water management as well as a suitable fuel feeding and system control. This challenge can be solved for stationary and mobile fuel cell systems with active components such as compressors, heaters, cooler or humidifier whereas for portable systems a minimum amount of peripheral elements should be used.

The most important functions of the peripheral devices for portable fuel cell systems are to start and stop the fuel supply for the fuel cell stack, ensure a safe pressure regulation and provide the appropriate air supply for cathode feeding and system cooling. The necessary devices like valves, pumps, fans or pressure reducers have to be miniaturised in size and optimised in power consumption. Automatic operation of such a system requires several components which, in some cases, are not commonly available and thus need to be developed additionally.

Furthermore, the whole control system has to be further developed and integrated in an embedded system. The benefits of an integrated electronics, although adding complexity, are a perfect match of the various devices, a control of the fuel cell aiming at a highly humidified membrane and simultaneously at the least chance of water droplet formation. Additionally, the total power management with respect to the adaptation of the fuel cell system to the respective electronic device, e.g. an adjustable controlled output voltage level, needs to be implemented. Since the profile of the electrical load of electronic devices varies a lot, the fuel cell system must be accommodating to the needs of the respective system. Varying profiles are a challenge for sizing a fuel cell system. A hybrid system combining a fuel cell with a battery or a supercapacitor is considered as an optimal solution for such boundary conditions.

If the fuel cell system is to be used as a battery replacement in electronic consumer devices, the safety standards of batteries have to be obeyed. Even under abuse, no dangerous situation may occur, as is the case for the common types of batteries like Ni/Cd, Ni/MeHx or Li-Ion. Any kind of maintenance is excluded, however recharging the fuel cell system by simply replacing an empty storage container by a full one is the only exception.

According to some published calculations, the cost of a fuel cell system would be roughly on the same order of magnitude as a battery if mass production is assumed /1/. Important innovations in this field will be the minimisation of noble metals in the catalyst layer, cost effective production of bipolar plates due to hot pressing or injection moulding, automated mounting and bonding technologies and less expensive peripheral elements.

Fuel choice

The fuel choice is limited by several factors such as the volumetric and gravimetric energy density, the weight and lifetime of the fuel container, the conversion efficiency of the chemical energy to electricity, the safety of the fuel and fuel container during refuelling and transportation and finally the fuel distribution infrastructure. In the small power range, both hydrogen and methanol are very attractive fuels but also chemical hydrides and even the reforming of hydrocarbons are moving more and more into the focus of research activities. Hydrogen has the higher potential in terms of power density whereas methanol fuel cells dominate from the energy density point of view. A critical point is the transport of hydrogen or methanol in aeroplanes since they are classified as hazardous materials (Department of Transportation) or dangerous goods (UN). At the current status it seems that limited amounts of metal hydride or methanol (diluted in water < 24 %) will be allowed in the mid term on the base of exemptions for checked baggage (3).

Among the techniques for the storage of pure hydrogen - gaseous at high pressure, liquid at ñ253∝C and chemically bound in hydrides - the latter is the only suitable way to store hydrogen with an appropriate energy density in small units. Containers for high pressure or with a superisolation do not fit to the requirements for portable applications. Those who are in favour of pure hydrogen are hoping for the development of carbon nanostructures as an (weight) efficient medium for fuel cells. Although the concept seemed very promising in the mid-nineties causing a lot of attention, it is in the meanwhile very unlikely that carbon nanostructures will meet the high expectations of that time. (4)

With respect to hydrides, there are again two choices: 1) chemical compounds like CaH_2 which release hydrogen upon addition of water or 2) metallic alloys which are able to adsorb and desorb hydrogen upon changes of pressure and temperature.

Compounds such as chemical hydrides can only be used once and the synthesis procedure of these hydrides is a complicated chemical process. A mixture of water and Ca-hydroxide is the waste product which must then be recycled or disposed. As this reaction can only be started by adding water and does not stop before all the water is consumed, there are practical limits for the application. Another approach would be a hydrous $NaBH_4$-solution, which releases hydrogen upon contact with a Ru-catalyst.

Hydride materials, which can be charged and discharged reversibly, are metallic alloys. The composition of the alloy determines the temperature and pressure levels for the desorption and adsorption process. For portable applications, the temperature and pressure for the desorption process must be close to ambient. These type of alloys have been developed for many years, the partial replacement of La and Ni by other elements determines the properties.

The typical storage density of these hydride materials is 1.3 ñ 1.5 weight-% of hydrogen, corresponding to 180 l of hydrogen per kg of hydride material or 540 Wh/kg or 1920 Wh/l based on the lower heating value for hydrogen (excluding efficiency losses). Announcements of some companies indicate, that hydrides with 2 weight % of hydrogen will be available within the next years. In addition to the hydride material, there is a container, a filter and a valve to complete the storage system. They also contribute to the weight and size of the system indicating a lower limit for a reasonable size of the container. These hydride materials are considered to be the safest way to store hydrogen since the temperature decreases during discharging and the hydrogen release is decelerated accordingly. The alloys can be charged and discharged several thousands of times, depending on the purity of the hydrogen used for charging. The company HERA which was founded recently from a consortium consisting of GfE (Gesellschaft f¸ r Elektrometallurgie), Hydro-QuÈbec and Shell Hydrogen aims to develop, manufacture, market and sell a portfolio of safe and clean hydrogen storage products using metal hydrides. This step will definitely help setting up an hydrogen infrastructure.

Methanol, the simplest alcohol, is a liquid fuel which can be oxidised electrochemically in the presence of water. Methanol has a high energy density (3450 Wh/kg and 3000 Wh/l in 1:1 molar ratio with water, excluding efficiency losses), is easy to handle, is completely miscible with water and can be generated from a variety of sources such as natural gas, coal and even biomass. Furthermore, it is available in pharmacies at a low price. However, it is toxic and there is a certain leakage of methanol through the polymer electrolyte membrane (crossover) resulting in a poisoning of the cathode catalyst by the formation of a mixed potential. Another material problem is the slow anode electrocatalysis of methanol which requires significantly more costly noble metal catalyst than the direct hydrogen fuel cell. As a result of this, the power density of the fuel cell stack at room temperature is currently at least a factor of 5 smaller than that of a hydrogen fed fuel cell.

Small scale reformers offer the use of hydrocarbons with their high energy density at reasonable fuel costs (5). The striking feature is the world-wide availability of liquid fuels like gasoline, diesel or butane. Unfortunately, methanol is the only fuel which can be converted at intermediate temperatures of 250 ñ 300 ∞C into a hydrogen rich gas mixture. For all the other fuels, higher temperatures above 700∞C are necessary. The miniaturisation of the reformer itself and the catalyst development for the reforming reaction are investigated. In micro-channel reformers, complete conversion of various fuels could be achieved in very short contact times in the range of 20 ñ 50 msec. But the selectivity of the catalysts should be optimised with respect to the suppression of CO formation in order to reduce the size and weight of the gas purification unit. Another R&D-task is to cope with the sulphur problem in common diesel fuel.

Prototype systems

In the meanwhile, there are numerous universities, institutes and companies dealing with the development of fuel cell stacks and systems in the portable power range based on solid polymer fuel cells. Next to the published results, there are plenty of rumours and press releases, both of which do not reflect the precise state of technology. Additionally it can be assumed, that the major battery companies are involved with fuel cells since the technology is somehow similar and the target market as well.

The closest to commercialisation are free-standing systems as power supply units in the 10 to 100 W-range at several output voltage levels without any geometrical adoption to existing appliances. But on the other hand, the highest pressure is on fuel cell solutions for example for cell phones and laptops because for such applications, the limited energy density of existing batteries is a major bottleneck for the development of future devices. But since all technical challenges are accumulated for those systems, there is no commercial system in sight at the moment. Besides those consumer applications, there is a strong need for new power sources for military applications both for the individual soldier as well as for auxiliary power units (APUs) in the several hundred Watt-range. Here, there is also an increased interest for small reformer systems in all kind of power ranges due to the world-wide availability of gasoline and diesel.

As an example, some results of the Fraunhofer Institute for Solar Energy Systems ISE in Germany will be described briefly.

The Fraunhofer ISE startet research and development of small fuel cells in the mid nineties and as a first demonstrator, an external 20 W system based on the banded membrane technology powering a laptop was developed. In the meanwhile, a fully integrated fuel cell system (50 W_p)based on hydrogen was developed for the Korean institute ëClean Energy Technology, Incorporatedí (CETI). With this system, about the same energy density as with the rechargeable battery could be realized (Fig. 2), the total weight of the fuel cell stack is only 120 g.

Figure 2: Fully integrated fuel cell system with 50 W peak power, developed by the Fraunhofer Institute for Solar Energy Systems.

In 2001, the Fraunhofer Initiative Micro Fuel Cell which consists of 7 Fraunhofer Institutes with different technical background of was founded by the Fraunhofer ISE aiming at the convergence of the respective expertise like modelling, micro-actuators, conductive polymers as bipolar plates, system design, power management, micro-machining, mounting and bonding technology in order to cope with all challenges for the realization of different fuel cell systems. As a prototype system, a 10 W fuel cell system powering a digital camcorder was developed (Fig.3). Again, about the same volumetric energy density as the rechargeable battery could be achieved.

Figure 3: 10 W hydrogen fuel cell system powering a camcorder. This system was developed by the ëFraunhofer Initiative Micro Fuel Cellí

For this product, the whole production chain from bipolar plate manufacturing by means of hot pressing of conductive polymers (e.g.) to automatized stack production with adhesives and clamps was developed (Fig.4).

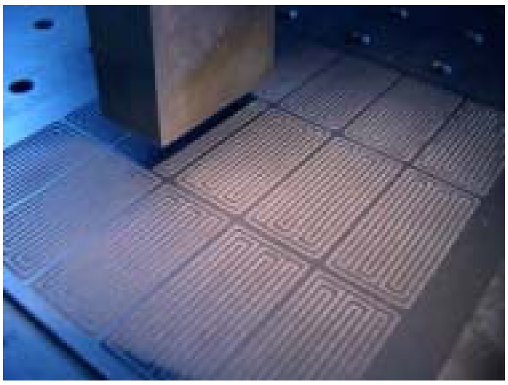

Fig.4a Bipolar plate production by means of ultrasonic machining

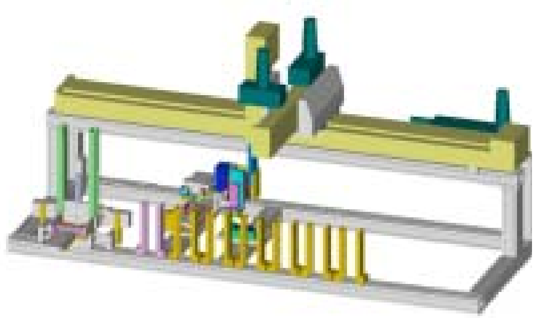

Fig.4b Fully automatted mounting unit for micro-stacks.

Summary

Portable fuel cell systems definitely enjoy an increasing popularity which arises from some striking inherent technological features combined with their applicability to mass market products. However, in order to avoid the mistakes which were made in the higher power range, it should be underlined that the technical challenges are tremendous and the direct competitors, the rechargeable batteries, are highly sophisticated and accepted by the customer. This setting is even more delicate when the relatively moderate overall budget is considered which has been spent so far on research, development and commercialisation of portable fuel cell systems. But since the pressure on the development of alternative power sources with very high energy densities is increasing enormously, portable fuel cells will definitely benefit from that. And, as a result of this, it is very likely that we will see the first fuel cell powered portable products on the market within the next years.

References:

(1) Chris Dyer, Journal of Power Sources 106 (2002) 31-34

(2) Christopher Hebling, Proceedings of the 7th Grove Fuel Cell Symposium, London, September 11-13, 2001

(3) Jerry Hallmark, Small Fuel Cells for Portable Power Applications, Washington, 2001

(4) Kaylene Atkinson, Fuel Cells Bulletin No. 38

(5) Patricia Irving, Proceedings of the Symposium on the Commercialization of Small Fuel Cells for Portable Power Applications, Washington, 2002, Knowledge Foundation, Boston