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A new approach to fuel cell investment strategy

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Abstract

Siemens fuel cell activities concentrate on solid oxide fuel cell (SOFC) and polymer-electrolyte-membrane fuel cell (PEM FC) development, and direct methanol fuel cell (DMFC) research. Commercial application has, to date, been achieved in the field of PEM FCs for air-independent propulsion. A specific development project is being conducted aimed at the verification of an innovative cell concept to match the competitive cost of PEM FCs. SOFC development aims at decentralized power and combined heat and power (CHP) plants. Following the success achieved in the 10-kW class, a first prototype system with a power rating of 100 kW is scheduled for the year 2001. Achieving a cost advantage over competitive technologies is to be seen as the driving force behind all efforts. © 1998 Elsevier Science S.A.

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1. Introduction

The fuel cell is today in the focus of interest as one of the most promising developments in power generation. The visions for the future use of this technology encompass the wide span from power supply for small electronic equipment with only a few watts up to power stations in the megawatt range for centralized power production.

Fuel cells have some advantages compared with existing energy supply systems, especially under environmental aspects. This leads to optimistic expectations that restrictions by law may push the fuel cell into the market against proven competitors.

Today, fuel cell development in general has reached a status where the technology can be demonstrated, but due to generally uncompetitive prices, a commercial market does not exist.

The vision of power supply in the year 20xx will still initially be based on fossil energy sources, using natural gas and coal and, may be nuclear energy. Additionally, renewable energies will gain an increasing market share with biomass power plants, wind and solar energy. Energy management via satellite and HVDC long-distance power transmission lines as well as energy storage systems and superconducting cables will take full advantage of the power plants. Fuel cells are expected to find their place in decentralized heat and power supply in this vision.

This presentation gives an overview of current Siemens activities, the status already reached and the goals for the future to commercialize the fuel cell in the scenario of power supply in the coming decades.

2. History of fuel cell development at Siemens

Before the actual status is presented, some key data on development in the past should be mentioned to give an overview of the different fields of activity at Siemens.

Looking at the historical background, the starting point was in 1965 with development of the alkaline fuel cell (AFC). As a final result, a 16-kW module was developed and used in various demonstration projects. The most successful demonstration to be mentioned was the U1 submarine equipped with a 100-kW AFC for air-independent propulsion (AIP). This submarine was tested by the German Navy in 1988 to their highest satisfaction. The AFC branch

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was abandoned at Siemens in 1992 after the Hermes space glider project was called off at ESA.

This success with AIP was in 1989 the starting point for development of the polymer-electrolyte-membrane fuel cell (PEM FC) for this application, for the PEM FC has some major advantages over AFC. PEM FC development resulted in a 34-kW module which has been series-produced since 1996. A minor project derived from this design was a small H_2/O_2 fuel cell which was integrated into the energy autonomous house of the Fraunhofer Gesellschaft in Freiburg, Germany, and used as part of a long-term storage system for about 2 years.

In addition to this hydrogen/oxygen application, some demonstration fuel cells using hydrogen with air were constructed with a view to specific applications such as a fork lift truck and a system to supply homes with heat and power. Some details are presented in the following.

With a view to significant cost reduction a 4-year research program was started in 1995 to develop the so called 'innovative low cost design' for PEM fuel cells. This projects focuses on verification of challenging price and performance goals as a basis for further decisions.

In the field of low-temperature fuel cells activities in direct methanol fuel cell (DMFC) research, which started in 1992, should be mentioned. They are at the basic research stage and have to date not produced a demonstration project.

Investigation of the solid oxide fuel cell (SOFC) started in 1987 with a project definition phase. Development had begun in 1990 with a planar SOFC design using metallic bipolar plates to separate the multiple cell layers in the stack. As early as 1995, a 10-kW laboratory stack was successfully tested with hydrogen and oxygen, with a remarkably high power density compared to other developers. Activities in this field are being continued intensively.

In conclusion, Siemens is currently developing two main types of fuel cells which are aimed at quite different fields of application, with commercialization expected within the next decade:

1. Polymer-Electrolyte-Membrane Fuel Cell (PEM FC);
2. Solid Oxide Fuel Cell (SOFC).

3. PEM FC status

PEM FC activities at Siemens cover different fields of application. The main line is concerned with the air-independent propulsion system. Development of the 34-kW module for this purpose was finished in 1996 with the successful testing of three prototype modules. Series production of this module type has subsequently been started in order to equip the U212 class of submarines for the German Navy, which are under construction. One prototype module was continuously tested for more than 1500 h.

Technical data of an AIP module with a nominal power output of 34 kW are given in Table 1.

The PEM FC in AIP application has to be seen under technological aspects. The advantages using fuel cells in submarines are mainly to be seen in prolongation of the air-independent operating time, which provides an advanced quality for small submarines without a nuclear power source.

Further advantages of the fuel cell technology are

1. high power density;
2. favorable overload behavior;
3. low degradation of voltage vs. operating time;
4. long useful life;
5. favorable temperature and load change behavior;
6. no regeneration phase after shutdown—ready to start immediately;
7. no liquid, corrosive electrolyte;
8. favorable efficiency.

Comparable competitive technologies such as closed-cycle diesel engines or sterling engines are likewise under development and are not expected to gain a leading position. In general, the fuel cell looks likely to have the better attractiveness in this field.

The AIP market of course will remain a niche market, but the PEM FC will keep its leading position due to technological advantages and may become a standard for modern submarine fleets.

The AIP application uses pure hydrogen and oxygen. For terrestrial applications the use of ambient air instead of pure oxygen is an unavoidable prerequisite. At Siemens, three quite different demonstration projects were performed or are in progress, and these are presented in the following sections.

3.1. Fork lift truck

This project was performed on behalf of Solar-Wasserstoff-Bayern GmbH (SWB). The aim was to equip a fork lift truck originally supplied with batteries with a PEM fuel cell in such a way that all components including gas storage tank (metal hydride storage) and waste heat removal system would be integrated within the dimensions of the battery

Table 1

Technical data of an AIP module with a nominal power output of 34 kW

Power output	30–40 kW (55 kW for short periods)
Voltage	50–55 V DC
Efficiency at rated load	59%
Efficiency at 20% load	69%
Operating temperature	80°C
H_2 pressure	2.0 bar, abs
O_2 pressure	2.3 bar, abs
Dimensions	Height: 471 mm
	Width: 471 mm
	Length: 1.431 mm
Weight (without module electronics)	Approx. 650 kg

compartment. It should also be possible to operate the power source as a stationary stand-alone system at an electronic load for further testing.

The 75-cell stack with a gross power output of 18 kW was derived from the AIP design. The nominal net output of the power supply system is 10 kW at 48 V DC. Some additional technical data are included in Table 2.

The fork lift truck is equipped with a redundant control system including a watchdog and an H_2 sensor function for safety purposes, and is certified by the German Technical Inspectorate (TÜV). The system was put to operation and delivered to the customer in August 1997.

3.2. Energy for homes

In this demonstration project the supply of heat and power for a detached house provided by a PEM fuel cell system was investigated. This project was performed by the Siemens Technology Group. The system set-up consisted, on the one hand, of the PEM FC system to supply heat and power and, on the other, of the simulation of realistic heat loads modeling a house installation as closely as possible to the real situation.

The fuel cell system contained a stack with 75 cells of $200 \times 400\ mm^2$. Some essential data concerning the fuel cell are shown in Table 3. Some data for the reference house are given in Table 4.

The fuel cell was successfully put into operation in March 1997. The project has, in the meantime, been frozen until a further assessment is performed with regard to the commercial prospects of this application within the existing infrastructure and due to target costs.

3.3. Low-floor city bus

The bus project was started in October 1996, with the aim of putting a low-floor city bus equipped with a 120-kW PEM fuel cell system into operation in 1999. The project is being sponsored by the Bavarian government. The project partners are MAN Nutzfahrzeuge AG, MAN Technologie AG, Linde AG, Ludwig Bölkow Systemtechnik GmbH, and the Siemens Transport Systems and Power Generation Groups.

The bus with a rated power of 120 kW will contain four modules arranged together with the system components in the rear of the bus. The fuel is stored as pressurized hydrogen in lightweight cylinders on the top of the bus. Technical data for the bus are given in Table 5.

Table 2

Additional technical data for the 75-cell stack fuel cell for the fork lift truck

Net power output	10 kW
Nominal voltage	48 V DC
Operating temperature	60°C
Air pressure	1.5 bar, abs
H_2 pressure	2.0 bar, abs
Dimensions of the FC module	H:410 mm W:410 mm L:660 mm
Dimensions of the power source	H:920 mm W:800 mm L:1020 mm

Table 3

Additional technical data for the 75-cell stack fuel cell for the home

Net power output	5.5 kWe
Heat output	8.0 kWh
Voltage	48–62 V DC
Rated current	163 A
Dimensions of the FC module	$728 \times 235 \times 440\ mm^3$
Air pressure	1.5 bar, abs
H_2 pressure	2.0 bar, abs

So much for demonstration projects with PEM fuel cell stacks derived from the AIP design.

To meet the very challenging target costs indicated by combustion engines in the field of mobile and stationary applications, the AIP design does not have the cost reduction potential to succeed in this field. As a consequence the development of an ‘innovative cell concept’ was launched which is being sponsored by five Siemens Groups. The main objectives of this project are:

1. cost-saving and production-oriented construction;
2. avoidance of additional seals;
3. suitable for H_2/air operation;
4. heat removal by air cooling.

One main feature of this design is the fabrication of stand-alone single cells. One cell consists of two punched and embossed sheet metal plates with the membrane electrode assembly in between. The actual size is $100 \times 100\ mm^2$. This assembly is fixed and sealed by clamps around the edges. The single cells can be tested and operated separately before they are assembled to form a stack. Cooling is provided by air which is directed through the free space between the cells.

The aim of this project, which will end in 1999, is verification of the concept that the following goals in mass production are within reach:

1. 200 DM/kW;
2. 2.5 kg/kW;
3. 2.5 l/kW.

Additionally some remarks should be given about the direct methanol fuel cell (DMFC) activities, which directly uses a liquid methanol/water mixture at the fuel side.

The DMFC is today at the research stage and is far from being comparable to the status the PEM FC already has reached. The problems which have to be resolved are characterized by:

1. enhancement of the electrochemical process;
2. development of appropriate electrolyte materials;
3. development of more effective catalyst materials;
4. leakage of the PEM membrane for methanol;
5. sufficient increase in power density.

Table 4

Technical data for the reference house

Detached house; living area	Four persons, 150 m^2
Utilization	365 days p.a.
Room heating requirement	15 000 kWh
Hot water requirement	3000 kWh
Thermal peak load	11.7 kWh
Power requirement	4870 kWh
Mode of operation	Heat controlled

In conclusion, the demonstration using extended stacks with sufficient power output is not expected to take place in the next few years. The horizon for commercialization is not expected before 2010, although the DMFC would be very attractive for mobile applications avoiding the methanol reformer and directly using liquid fuel, which can easily be provided at gasoline filling stations.

4. SOFC development

The motivation to develop SOFC technology is mainly based on the fact that the efficiency of SOFC systems is considerably higher than that of those of competitive power generating systems.

Table 5

Technical data for the low-floor city bus

Vehicle	MAN Nutzfahrzeuge AG
Model	Low-floor bus NL223
Length	12 m
Weight	18 t
Vehicle drive system	Siemens AG, Transport Systems
ELFA drive system	Two asynchronous motors, model 1 PV5135
Maximum drive output	2 × 75 kW via summation gearbox and cardan shaft to rear axle
Traction motor converter	IGBT pulse-controlled inverter, model ELFA-DUO
Fuel cell system	Siemens AG, Power Generation
Fuel cell modules	Four modules
Rated power output	120 kW
Voltage at rated power	Approximately 400 V
Operating temperature	60°C
Operating air pressure	$<$1.5 bar, abs
Air-air ratio	2
Hydrogen consumption at rated output	8 kg/h
Hydrogen storage system	MAN Technologie AG
Maximum filling pressure	250 bar
Cylinders	12
Total capacity	Approximately 2200 l
Operating range	$>$300 km
Hydrogen fueling system, periphery	Linde AG
Gas tract in vehicle	Main shut-off cock, fueling coupling, pressure reducer etc
Hydrogen filling station	Storage and fueling system including safety devices

Table 6

Data for the laboratory configuration of the stack configuration

Layers	80
Cells per layer	16
Active surface	2 m^2
Volume	20 dm^3
Maximum power at	Maximum power at
950°C	850°C
10.7 kW (H_2/O_2)	8.4 kW (H_2/O_2)
5.4 kW (H_2/air)	4.1 kW (H_2/air)
Current density	0.6 A/cm^2
Gas utilization(at max. power)	40–50%

Especially in the target field of power plant capacity from 100 kW to 50 MW, efficiency is about 50% for small SOFC plants, which would be operated at ambient pressure. For pressurized systems with an additional downstream gas turbine the net electrical efficiency is expected to attain 70%. The challenge is to come as soon as possible to a commercially competitive system design to enter the market in the range up to 50 MW. It is clear that the development of pressurized systems later with a gas turbine will be the second step. However, the prospect of success is also visible for small low-pressure systems from the technological and commercial point of view.

The Siemens design is primarily characterized by the following features:

1. planar design of the cells;
2. multiple cells per layer;
3. metallic bipolar plates between the layers.

The membrane electrode assemblies (MEA) measuring 50 × 50 mm^2, which are manufactured by Siemens were tested in different stack assemblies with up to 16 MEAs per layer and 80 layers per stack. This stack configuration was tested in a laboratory set-up with the data in Table 6.

The advanced stack design uses MEAs with an increased area size of 100 × 100 mm^2 with nine MEAs per layer.

The production capacity per year achieved to date is in the order of 30 000 MEAs of the 50 × 50 mm^2 and 7 000 MEAs of 100 × 100 mm^2 type.

Besides the development of the main components such as the MEAs, bipolar plates and the testing of stack assemblies, a test facility for testing stack assemblies up to 20 kW under real conditions was set up in parallel. This test facility contains all the high-temperature components necessary for a complete power module operating under real conditions, i.e. anode and cathode gas heat exchangers and the control system based on SIMATIC S5. This work has to be seen in the context with the planning of a 100-kW demonstration plant, which is scheduled for the year 2001.

The 100-kW demonstration plant is designed to fit into a 20-ft container, housing all the components for a complete power module fed with natural gas and supplying power to the grid as well as heat.

The tasks which have to be solved from the technical point of view are mainly in the fields of:

1. enlargement of the electrode area;
2. increasing long-term stability;
3. reduction of the operating temperature (i.e. price reduction of the BOP);
4. improvement of sealing techniques;
5. improvement of coating procedures;
6. improvement of power density by pressurization together with high electrical efficiency.

The roadmap for market introduction of the SOFC is assumed as follows:

1. 2001: first 100-kW demonstration plant;
2. by 2005: small series of demonstration plants;
3. 2005: market entry with plants of about 250-kW capacity;
4. 2010: market entry with pressurized systems, provided the milestones are reached on schedule and mass production of stack components is launched by 2005.

The SOFC is seen to represent a key technology for decentralized power supply in the future.

The market segment for introducing SOFC in the mid-term vision is the combined heat and power (CHP) supply with decentralized compact units providing heat and power near to the end user.

In the long-term vision, pure power production at a highest efficiency with decentralized power stations shows significant advantages over competitive technologies.

The budget to perform the necessary steps is currently at Siemens in the order of 12 million DM per year.

5. Preconditions for market penetration, especially of SOFC

Today, interest is focused mainly on technical development with particular attention paid to the performance of demonstration set-ups and plants, which are being implemented with increasing frequency. However, the prospect of success of the fuel cell will be mainly dominated by infrastructural boundary conditions and commercial aspects.

In the near future, the fuel cell used in stationary applications will have to find its place in the existing power supply structure which is dominated by fossil energy sources. Structural changes are expected to take place in this field, leading to increasing decentralized power supply.

In the case of the fuel cell, the availability of natural gas will in particular be a precondition. The market for SOFCs will therefore preferentially develop in countries with sufficient natural gas supply and a well-structured gas distribution network. In this scenario it is assumed that natural gas will achieve essential progress world-wide. The mid-term regions to focus on are expected to be in Western Europe, Eastern Europe, North America and Japan.

To be successful the fuel cell must be able to survive in the competition of the market against proven technologies. In the CHP sector these are gas combustion engines, diesel combustion engines and to an increasing extent newly developed small gas turbines combined with generators. In the pure power supply market gas-fired power stations, combined-cycle power plants and also coal-fired power plants are the competitors. Only if the fuel cell, irrespective of type, is able to provide the customer significant advantages in terms of life-cycle costs and in terms of equivalent power generating costs, the market share will be in accordance with today's developer expectations.

6. Conclusions

The long-term success of the fuel cell will depend on broad-based market entry, not only on the penetration of niche markets, for mass production is a prerequisite for achieving competitive costs. The potential of the existing technologies regarding cost reduction and increased efficiency should be kept in mind in this scenario, whereas environmental aspects may play a minor role because they only will be of consequence if overall competitiveness is reached. Environmental advantages by themselves do not have the potential to overcome a significant price gap.

The years to come will show whether today's efforts and expenditures will transform the visions into reality in the way we expect.