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FUEL CELLS IN EUROPE

P. ZEGERS

Commission of European Communities, rue de la Loi 200, B-1049 Brussels (Belgium)

Introduction

Ten to fifteen years ago fuel cell research and development (R&D) in Europe flourished with extensive R&D on phosphoric acid (PAFC), molten carbonate (MCFC), solid oxide (SOFC) and alkaline (AFC) fuel cells.

Around 1975, most of these activities had stopped with the exception of AFC. The year 1985 was a turning point where R&D on most fuel cell types started again in fuel cell R&D programmes in the Commission of European Communities (CEC), F.R.G., Italy, the Netherlands, Spain, Norway and Switzerland. Since 1985 much has happened:

- A 1 MW PAFC plant will be operational in 1991 in Milan, Italy
- A 1 kW ER-MCFC became operational in July 1989 in the Netherlands
- Promising results have been obtained in the development of direct methanol fuel cells (DMFC) for small-scale application and transportation
- Three projects with a strong industrial participation will start to develop a 10 kW MCFC plant with coal gas and two 1 kW SOFC units, fueled with methane.

Before discussing European fuel cell research in more detail, some general aspects of fuel cells are discussed.

Fuel cells as a major technology for energy conversion

At present, energy conversion is 90% based on combustion of coal, oil and gas, and combustion processes still have a long way to go. The efficiency of these processes however is often not very high (Carnot), their pollution is considerable and the problem of CO_2 is becoming increasingly important.

A change to other more efficient and less polluting systems should therefore be seriously considered. Electrochemical energy production (fuel cells) and storage systems (secondary batteries) are an interesting possibility.

These systems could cover many areas.

- Large (MW) scale power production with efficiencies up to 70% (instead of 40% obtained with steam turbines); these fuel cells may also be used in seaships (PAFC, MCFC, SOFC).
- Cogeneration systems which produce power with 50% efficiency and in addition industrial process heat at 600 or 900 °C (MCFC, SOFC).

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TABLE 1

Specification of primary energy use in Europe (1030 million tonne oil equivalent)

Energy use	Proportion of total (%)	Fuel cell types
Buildings	43	
Heating	25.8	PAFC (80 - 120 °C)
Electricity	17.2	PAFC
Industry	37	MCFC (650 °C)
Electricity	15.5	SOFC (1000 °C)
Process heating	21.5	
Transport	20	PAFC DMFC (70 - 100 °C) SPFC (70 °C)
Seaships	±18	PAFC MCFC SOFC

- Cogeneration systems which produce electricity at 40 - 45% efficiency and heat at 80 - 120 °C for heating of buildings (PAFC).
- In transportation, electrical vehicles with fuel cells may achieve efficiencies which are 2 to 3 times higher than petrol engines (DMFC, PAFC, AFC).

From Table 1, which gives a specification of the primary energy use in Europe, it is clear that cost effective fuel cells can play a major role in all energy demand sectors.

Some data on fuel cells and factors influencing their application

The major components of a fuel cell power plant are given in Fig. 1. The fuel processor (reformer for methane or naphtha and coal gasifier for coal) transforms fuel into hydrogen gas which in its turn is converted into electricity and water in the fuel cell. A large variety of systems is possible, depending on the type of fuel cell and on how the waste heat of a fuel cell will be used: cogeneration, internal reforming, bottoming cycle. Much work will have to be done on the optimization of a fuel cell plant for particular applications. Some data on the most important fuel cell types are given in Table 2.

Contrary to combustion engines, fuel cells have high partload efficiencies (for some fuel cells such as PAFC and DMFC partload efficiencies are even higher than the fuel load efficiency). Generally, a rapid power variation is possible for MW size plants (10 → 100% in 30 s). Finally, the fuel utilization in the fuel cell is 80 - 85% and the remaining 15 - 20% H_2 will have to be used in an efficient way.

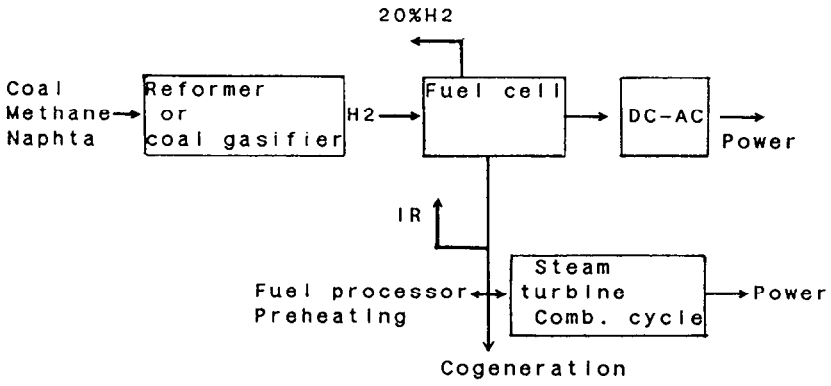

Fig. 1. Schematic layout of a fuel cell plant.

TABLE 2

Fuel cell types and properties

Fuel cell power plant	Efficiency methane → electricity (compl. plant) (%)	Temperature waste heat (°C)	State of art
AFC	35 - 40	60 - 80	10 - 100 kW
PAFC	35 - 42 (47)	80 - 120	1 - 4 MW
MCFC	65 - 70	500 - 600	20 kW
SOFC	65 - 70	700 - 900	5 kW
DMFC	methanol → power 40 - 50	60 - 100	200 W

Internal reforming

An important concept for fuel cells fueled with methane and operating at temperatures higher than 600 °C (MCFC and SOFC) is the concept of internal reforming (IR). Here, waste heat of the fuel cell is used to transform methane into hydrogen *in* the fuel cell. In this way, an external reformer is not needed which can lead to a 30% cost reduction. In addition, the cooling requirements are lower which leads to an additional cost reduction. The efficiencies for IR fuel cells are generally somewhat higher than fuel cells which use external reformers.

Problems with internal reforming mainly arise for MCFC which require reformer catalysts due to the fact that the waste heat is available at 600 °C and the reforming temperature for methane is around 800 °C. Much R&D is still needed to find suitable catalysts which can resist the very corrosive environment of MCFC. SOFC which operate at 1000 °C give less problems.

Modularity

Modularity is another important topic. A modular system obviously has advantages:

- The size of the installation can be adapted to the demand and this leads to reduction in capital cost
- Dispersed installation (e.g. in towns) is possible due to the low pollution of fuel cells and their modularity; this leads to lower power distribution costs

The extent of modularity however depends very much on the type of fuel cell power plant. In a coal gasifier with a fuel cell and a combined cycle, both the coal gasifier and the combined cycle have a strong economy of scale whereas only the fuel cell (with only 20% of the total cost) is modular. On the other hand, a methane fueled internal reforming fuel cell with only a small part of the electricity delivered by a steam turbine has a strong modular character.

A methane fueled fuel cell therefore can be designed for both modular and less modular applications. A coal fueled fuel cell plant generally has a rather strong economy of scale.

Pollution

Pollution in fuel cells is generally an order of magnitude smaller than for combustion systems. Of the two main components the fuel cell itself contributes very little to pollution; the main source of pollution is therefore the reformer or the coal gasifier.

Methane reforming occurs at 800 °C for which heat is delivered by a combustor which produces most of the NOx. With proper design of the burner NOx pollution can be brought down to 5 ppm. In the case where an internal reforming is used a combustor is not needed and the NOx pollution can be reduced to 1 ppm. SO_2 pollution is generally negligible and the hydrocarbons amount to 3 - 30 ppm. Figure 2 gives a comparison of the pollution of conventional and fuel cell power plants.

When *coal* is used, the fuel processor is a coal gasifier which transforms coal into a hydrogen rich gas. Also in this case the coal gasifier is the main cause of pollution. This pollution however is considerably lower than coal combustion of powdered coal. In fact, several countries consider replacing powdered coal combustion by coal gasifiers (with a combined cycle) for environmental reasons. If coal gasifiers will be used in future fuel cells may become very attractive from the point of view of cost, pollution abatement (a combined cycle produces NOx and a fuel does not) and energy saving. Data for NOx and SO_2 in gram per GJ electricity produced, are given in Table 3. The low value of SO_2 for MCFC plants is due to the fact that the sulfur tolerance for MCFC is 1 ppm and the gas from the coal gasifier has to be desulfurized to that level. The hydrocarbon content of exhaust gases in coal fueled fuel cell plants is negligible.

A rough cost estimate of NOx, SO_2 and CO_2 extraction is given in Table 4.

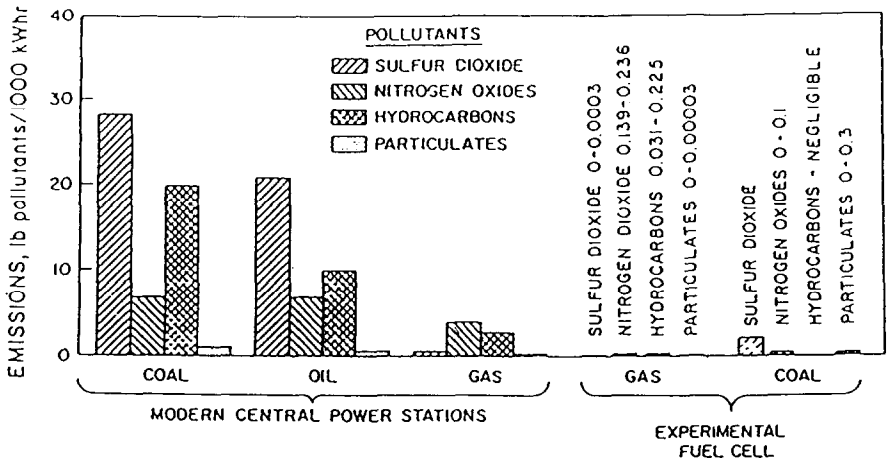

Fig. 2. Comparison of power system emission.

TABLE 3

NOx and SO_2 pollution in coal fueled power plants

	Coal combustions	Coal gasification	Coal gas + PAFC	Coal gas MCFC	Coal gas SOFC
NOx (g/GJ)	150	20	1.6	1.6	1.6
SO_2	1000	24	24 (24 ppm)	1 (1 ppm)	24 (24 ppm)

TABLE 4

Cost of CO_2, NOx and SO_2 extraction

	Coal combustion	Gas combustion	Coal gasification
Cost CO_2 extraction	5 ct/kW h[a]	3	2
Cost NOx + SO_2 extraction	2 - 4 ct/kW h		

[a]Dutch currency 235 ct = 1 ECU.

Finally, the pollution from fuel cells used in *transportation* can be expected to be very low. Fuel cells such as AFC, using hydrogen as a fuel, have no pollution at all. Methanol fueled fuel cells where methanol is directly oxidized or is transformed into hydrogen by internal reforming, have extremely low pollution levels. Methanol fueled PAFC with an external methanol reformer can also be expected to have the highest pollution. Comparison of a methanol PAFC system and an internal combustion engine is given in Fig. 3.

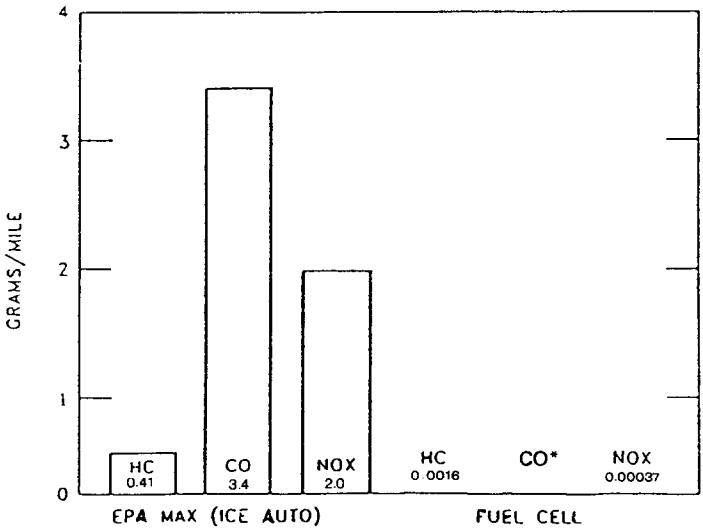

Fig. 3. Comparison of pollution levels for ICE and fuel cell driven cars (*CO not detectable with equipment sensitivity of 100 ppm).

Fuel cell R&D in Europe

An overview of European fuel cell R&D is given in Table 5. In Europe about 21 MECU/year is spent on terrestrial applications and 9 MECU/year for space applications.

European fuel cell R&D is generally following the lines given below.

- Europe should carry out R&D on all major fuel cell types for large-scale power production (PAFC, MCFC, SOFC). MCFC and SOFC seem more power production (PAFC, MCFC, SOFC). MCFC and SOFC seem more attractive due to higher efficiencies and higher waste heat temperatures. The technical barriers may however turn out to be insuperable and PAFC may increase its efficiency in small steps to 50%. At present, therefore one cannot say that there is a winning concept and R&D on all three fuel cell types is needed.
- CEC and national programmes should try to be complementary.
- Collaboration between all European fuel cell programmes should be promoted.

PAFC

The situation in Europe on PAFC may be characterized as follows:

- Europe has no PAFC stack producers
- PAFC know-how is available in Europe with companies such as Johnson Matthey and AEG
- Europe is strong in reformers (Haldor Topsoe, KTI) and a.c.–d.c. conversion

TABLE 5

European fuel cell programmes

	Start of programme	Duration (years)	Budget (MECU)	Fuel cell types
CEC	1989	3	25 (CEC 50%)	SOFC MCFC DMFC PAFC SPFC
Netherlands	1986	5	30	MCFC PAFC
Italy	1986	5 (a new 5 year programme is being prepared)	40	PAFC MCFC
F.R.G.		2 MECU/year		SOFC AFC
Spain	1988	5	15	MCFC
Norway	1988	5	3.5	SOFC
Switzerland	1988	3	4.5	SOFC
ESA	1988	2	18	AFC

This situation lead to a concept where European companies design and construct PAFC plants which have Japanese or U.S. PAFC stacks but where all other components are delivered by European manufacturers.

A major project is the construction of a 1 MW PAFC pilot plant in Milan, Italy by Ansaldo and Haldor Topsoc with stacks from the U.S. company IFC. This project is funded by the Italian FC programme with some financial support from the CEC.

Four 25 kW PAFC pilot units are being constructed by KTI with Italian, Dutch and CEC funding; the stacks will be delivered by Fuji.

MCFC

Dutch, Italian and CEC programmes on MCFC started in 1986 (Spain started in 1989). Before that date know-how on MCFC in Europe was very small.

In the Netherlands, ECN started a technology transfer programme with I.G.T. from the U.S., which was very dynamic and well structured. This lead to the operation of a 1 kW ER-MCFC unit in July 1989. In the future, 2.5 and 10 kW pilot units are planned in 1990 and 1991 respectively. The participation of an industrial partner is a key to the continuation of this programme. In the period from 1986 to 1991 30 MECU will be spent on Dutch MCFC research.

In Italy, R&D is following the same lines with stack development up to 10 kW MCFC units during the next three years and basic R&D on new cathode materials, nickel dissolution, corrosion problems, etc... ENEA is responsible for the overall management of this programme in which ANSALDO, CISE, CNR and a number of universities participate. For the period 1986 - 1989 around 5 MECU has been spent.

CEC, MCFC R&D started in 1986. During the first three years, research was focussed on basic R&D. An important task of the CEC here was to promote collaboration between European fuel cell programmes in particular in the field of basic R&D. In 1989, a new three-year programme was defined which includes:

- Basic R&D
- Development of a 1 kW internal reforming MCFC stack
- Development of a 10 kW MCFC pilot plant for coal gas

The total cost of this programme is 8 MECU of which the CEC contributes 40%.

Spain has started a 13 MECU five-year MCFC programme this year.

SOFC

At present SOFC work in Europe is carried out in the CEC, F.R.G., Norway and Switzerland. In Italy, a programme is being prepared. Know-how in Europe is comparable to that in the U.S.A. and Japan due to:

- Large SOFC programmes in the past (e.g. BBC, F.R.G.)
- Extensive work on high temperature electrolyzers which are closely related to SOFC (Dornier, F.R.G.)

In Europe industrial interest in SOFC is strong. This is possibly due to the fact that SOFC offers good possibilities by combining SOFC with existing power production technologies such as steam turbines or combined cycles.

The CEC started a two-year exploratory SOFC programme in 1987. Basic research was carried out to develop new electrode and electrolyte materials. Five SOFC concepts (2 honey combs and 3 flat plates) were also investigated. Finally, a market and a system study were carried out.

The market study by GEC was focussed on two applications:

- 200 kWe units for industrial cogeneration
- 200 MWe SOFC + combined cycle plants for power production

For a three-year period (1997 - 2000) a market of 50 - 100 MWe is predicted for the 200 kWe cogeneration units. Until 2015 a total SOFC market of 80 000 MW is expected. Most promising markets are F.R.G., U.K., Italy, Spain and the Netherlands. The expected efficiency and cost is given in Table 6.

The system study carried out by TNO investigated a 200 kWe cogeneration unit and a 100 MWe power plant consisting of a SOFC with a steam turbine bottoming cycle. The study investigated different SOFC options: ER or IR SOFC and different systems where the contribution of the steam

TABLE 6

Efficiency and cost of SOFC plants

	Efficiency (%)	Cost with present state-of-the-art (ECU/kW)
200 kWe CHP	80 (electricity + heat)	900 - 1000
200 MWe	70 electricity	800 - 900 (including combined cycle)

turbine bottoming cycle in the total electricity production varied from 12% to 40%.

The studies lead to the conclusion that cost effective SOFC can be developed with existing materials. A SOFC development plan was developed with the following targets:

- 2 × 1 kW SOFC units in 1992
- 1 or 2 × 20 kW SOFC in 1995
- 200 kWe cogeneration unit in 1997

The ongoing CEC SOFC programme (1989 - 1992) includes the following topics:

- Construction of a 1 kW SOFC stack with flat plate cells and metal bipolar plates (Siemens)
- Construction of a 1 kW SOFC with a modified tube concept (ABB)
- Basic R&D on electrodes and electrolytes
- Construction of a 100 W flat plate SOFC unit with a ceramic bipolar plate (Imperial College)

The total budget for three years is 12 MECU of which 50% is paid by the CEC.

SOFC R&D is also carried out in F.R.G. (tube type SOFC), Norway (thin-film electrolyte SOFC) and Switzerland.

Fuel cells for small-scale power plants and transportation

Fuel cell applications for transportation have the advantage that they can lead to efficiencies which are two to three times better than petrol engines and that the pollution is more than one order of magnitude smaller. The problem however is that the cost is around 500 - 1000 $/kW which, for a 40 kW car, is far too expensive. FC driven electrical cars however may have a chance due to:

- More severe environmental regulations (e.g. no ICE cars in the center of towns such as Rome and Milan)
- R&D aiming at a strong cost reduction of fuel cells

The CEC programme is focussed on cost reduction and has the following objectives:

- Development of methanol fueled fuel cell concepts where the methanol reformer can be deleted; this could lead to a 50% cost reduction and a much less bulky fuel cell plant
- Increase the current density, to reduce cost per kW
- Development of a fuel cell concept which allows cheap mass production
- Reduce the amount of precious metal catalyst

From 1985 to 1988 CEC research was investigating two ways to delete the methanol reformer:

- Development of a direct methanol fuel cell (DMFC)
- Development of methanol internal reforming fuel cell (IR-SPFC) operating at 300 °C.

This research lead to the development of a new catalyst which allowed operation of DMFC for 4000 h without poisoning of the catalyst.

R&D on IR SPFC, focussed on development of suitable solid electrolytes operating at 300 °C, was less successful. Several electrolytes have been developed but they could not be used at temperatures higher than 150 °C.

Future CEC research 1989 - 1992 will continue work on DMFC; the work on IR SPFC has been stopped. The objective is to develop DMFC with solid electrolytes operating at 100 to 150 °C with 100 - 150 mA/cm^2, 0.6 V and less than 1 mg precious metal loading per cm^2. It is hoped that this concept will lead to cost reductions which will allow DMFC to be competitive for small-scale stationary applications in the medium term and for transportation in the long term.

Other concepts such as H_2–air solid polymer fuel cells are being investigated in F.R.G. (Siemens) and Italy (de Nora).

Work on alkaline fuel cells has been carried out in Europe for many years. Siemens developed a H2-O2 AFC of 7.5 kW with a mobile electrolyte. AFC are also used in military applications (submarines). Elenco (Belgium) has a small pilot production facility for H2-air AFC (2.5 MW/year) and is developing a hydrogen fueled AFC of 75 kW for integration in a bus for public transport in Amsterdam.

The European Space Agency has an extensive programme on AFC for space applications with 18 MECU for a period of two years (1988 - 1989) which is reported in more detail by Baron on p. 207.