EUROPEAN COMMISSION

DIRECTORATE GENERAL XII: SCIENCE, RESEARCH AND DEVELOPMENT –
DIRECTION ENERGY
DIRECTORATE GENERAL XVII: ENERGY – DIRECTION ENERGY TECHNOLOGIES

A TEN YEAR FUEL CELL RESEARCH, DEVELOPMENT AND DEMONSTRATION STRATEGY FOR EUROPE

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EXECUTIVE SUMMARY

BACKGROUND

Fuel cells are electrochemical systems which convert primary energy into electricity at up to 60 or 65 % efficiency with very low pollutant emissions. Furthermore, heat rejected in the process can be used for different on-site thermal consumption which makes fuel cells suitable for combined heat and power generation for buildings and industry. With a growing tendency towards decentralized power generation, fuel cells will be particularly attractive for small scale combined heat and power generation located at users sites.

Fuel cells produce electricity by allowing hydrogen to come into contact with oxygen. Oxygen is taken from air. Hydrogen can be obtained by conversion of currently available primary sources such as natural gas, oil, coal or biomass. It can also be obtained by electrolysis of water using stand-by electricity from photovoltaics or wind energy.

Fuel cells can be used for electricity production, cogeneration for buildings and industry, road transport, ships, trains, etc. A major advantage is the very low pollutant emission which occurs only at the hydrogen production step. Zero emission is achieved if hydrogen is available. With higher efficiency for electricity production, less CO_2 is released into the atmosphere. Additional advantages are: a good part load behaviour, short construction times due to a high level of modularity, efficient power production for small sizes down to 10 kW which is particularly suitable for decentralized power production.

Although fuel cells are universally applicable and represent a promising clean and efficient energy conversion technology, it should be kept in mind that a large R,D&D effort is still needed to solve technical and reliability problems and to bring the fuel cells cost down to acceptable levels. Although fuel cell technology remains a long term option for many applications, in view of the importance of this technology for energy saving and clean energy conversion, the impact it may have on employment in the long term and the industrial competition on a worldwide scale, a European fuel cell R,D&D strategy is highly desirable.

Such a European strategy is also needed in view of the considerable funds which are required and which may be as high as 1000- 1500 MECU for the next ten years. This is beyond the possibilities for individual industrial and national programmes. It is also important to bring together the many dispersed competences and disciplines required for fuel cell development, thus avoiding overlaps and allowing an efficient use of available European resources.

This R,D&D Strategy for fuel cells is elaborated by the services of the European Commission to outline the orientations along which R,D&D activities will be carried-out under the Fourth and Fifth Framework Programmes of community activities in the field of research and technological development. It is not the intention of this Strategy document to include any industrial promotional policy nor any technologies dissemination measures.

FUEL CELL STRATEGY FOR THE NEXT TEN YEARS

The proposed European fuel cell strategy for the next ten years will focus on those fuel cell types and applications which, in terms of cost, pollution abatement and availability, can compete with conventional systems and can reach commercialization within this time period. The strategy will ensure coherent R&D and Demonstration activities supported by the European Commission. To ensure a good dissemination and use of the fuel cell technology, research on social, cultural, behavioural, institutional and legal factors will be pursued to identify the best instruments and best practices for good social acceptance of the new technology.

The strategy will consist of the following elements:

1. R,D&D should focus on low temperature fuel cells which have a potential for a very low cost per kW. They are expected to find applications in cogeneration in buildings and transport in the medium term.
2. The feasibility of a fuel cell network which consists of a centralized hydrogen production and a number of decentralized fuel cell stacks will be demonstrated.
3. Meanwhile, R&D efforts on currently expensive high temperature fuel cells should be maintained to offer industrial cogeneration and large scale (MW size) electricity production in the long term.
4. The size of fuel cell stacks and stand-alone systems will be limited to around 200-300 kW. At this scale, conventional gas turbines yield low efficiency and are very expensive, while diesel engines cause pollutant emissions 3-4 orders of magnitude higher than fuel cells and are not suitable in urban areas. Additionally, the 40.000-hour demonstration cost for small 200-300 kW fuel cell systems will be within acceptable limits.

After this ten year period, when a number of fuel cell technologies of 200-300 kW have been successfully demonstrated and marketed, fuel cell plants of 10-100 MW size can be envisaged.

STRATEGY APPROACH

The proposed strategy consists of a two-stage concept where a close collaboration between services of the European Commission dealing with fuel cell R&D (JOULE, BRITE) and Demonstration (THERMIE) serves as a catalyst and nucleus for a closer collaboration between national and industrial programmes in Europe.

This strategy will be implemented with funds made available in the 4th and 5th Framework Programme for Research and Development. The selection and follow up of projects should be carried out in close collaboration with Member States and industry.

Out of a total required budget of 1000-1500 MECU, the indicative EC contribution for the next ten year should amount to 160 MECU. The allocation pace will depend strongly on the progress of the R,D&D which will be strictly monitored.

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STRATEGY DOCUMENT

INTRODUCTION

At the onset of the Fourth Framework Programme for community research and technological development, a strategy for fuel cell technology in the next ten years is developed jointly by the Directorate General for Science, Research and Development (DGXII) and the Directorate General for Energy (DGXVII).

This strategy will contribute to ensure coherence between R&D activities and Demonstration activities managed from the European Commission. These activities are meant to be complementary to National Programmes and in full respect of the principle of subsidiairity. This R,D&D Strategy also serves as a catalyst and nucleus for a close collaboration between public funds and industrial programmes.

To prepare for a good acceptance and use of the fuel cell technology, accompanying research on social, cultural, behavioural, institutional and legal factors will be pursued to identify the best instruments and best practices. Particularly, the safety aspects of hydrogen handling should be properly addressed.

BACKGROUND

1. Fuel cells are electrochemical electricity generators which can produce electricity at efficiencies which are higher than in conventional power production systems, and heat at temperatures between 80°C and 1000°C. The environmental impact is one to two orders of magnitude lower than in conventional systems. Fuel cells have a good part load behaviour, are easy to operate and require low maintenance since no rotating parts are needed. It is the best alternative for small scale (below 1 MW) decentralized electricity generation and in particular for combined production of electricity and heat. The technologies are presently too expensive and the reliability has to be demonstrated.

2. There are five types of fuel cells:

- Phosphoric Acid Fuel Cells (PAFC): at approx. 40% electricity production and 100°C heat temperature, PAFC are suitable for commercial or light industry applications. They are close to marketable conditions, pilot plants of 1 MW in Italy and of 11 MW in Japan have been built, but their cost is still high (4000 ECU/kW).
- Molten Carbonate Fuel Cells (MCFC) have approx. 55% net electricity efficiency, MCFC operate at 600°C and are appropriate for utilities and industrial applications requiring heat between 200°C and 600°C. A number of technical problems such as corrosion and reliability still have to be solved. It is expected that commercialization will take 10 -15 years. At present systems of 100 kW have been constructed.
- Solid Oxide Fuel Cells (SOFC) have a comparable efficiency and the same utilization sectors as MCFC. SOFC operate at 1000°C and are being tested at a 20 kW scale. Further material research and cost reduction will be needed. Commercialization will take 10-15 years.

- Alkaline Fuel Cells (AFC) operate at approx. 80°C and have been extensively used in spacecrafts and submarine. They are being tested at 80 kW to drive a European bus, using hydrogen as fuel.
- Solid Polymer Fuel Cells (SPFC) and Direct Methanol Fuel cells (DMFC) operate at 80°C-130°C and are suitable for transport applications and cogeneration (combined production of heat and power) in buildings. They are currently tested at a 10-100 kW scale. They offer potential for strong cost reduction and may be marketed in 5-10 years.

3. At the European Commission level, RTD initiatives have been implemented through JOULE and BRITE (DGXII) programmes with a total support of 27 MECU in the period 1992-1995. Research covers basic materials research, lifetime improvement, scaling-up of MCFC and SOFC, balance-of-plant studies, internal reforming of MCFC and SOFC and development of external natural gas/methanol reformers for SPFC in transport applications.

4. The THERMIE programme (DGXVII) has spent until now a total of 7 MECU for the implementation of PAFC and MCFC, especially for stationary electricity production or combined heat and power applications.

5. The overall spending on fuel cell R,D&D in Europe, taking into account EU, national and industrial programmes, amount to around 70 MECU/y; this is about half the funds which are being made available for fuel cell RTD and demonstration in Japan and the US.

6. A non-exhaustive list of main actors from industry and utilities in the field of fuel cells in the EU is given below:

Type of fuel cells	*Present situation*
High/medium temperature fuel cells (PAFC, MCFC, SOFC)	**EU actors**: Dasa, Dornier, Siemens (D); Haldor Topsøe (Dk); TGI (E); Ansaldo, ENEA, ENI (I); GEC, ICI, Rolls Royce (UK); ECN, De Schelde, Stork (NL) and the following utilities, British Gas, Ruhrgas, RWE (D), Elsam (DK), ENEL (I), Iberdrola (E), SEP (NL). **PAFC**: • Joint venture Ansaldo & IFC (USA) using US made stacks (1.3 MW installed in Milan), 11 MW built in Japan **MCFC**: • Joint venture of MTU & ERC (USA) for common research and production and of Ansaldo,BWE (E) & IFC (USA) using European made stacks. • European producer: BCN (NL), Ansaldo (I) (Up to 100 kW installed in US and Japan but technical problems. New 2MW started in US) **SOFC**: No joint venture.
Low temperature fuel cells (AFC, SPFC, DMFC)	**EU actors**: Elenco, Hydrogen Systems (B); Dornier, Siemens (D); De Nora, Fiat (I); IFP(F); Johnson Matthey, VSEL (UK). Near to market product with increasing interest from car manufacturers.
Reformers	Haldor Topsoe (DK) and KTI-MAN (NL, D) are world leaders. Other actors are Rolls Royce and CJBD (UK)

A COMMON EU STRATEGY

8. A common fuel cell strategy is highly desirable in view of the importance of this technology for energy savings and clean energy conversion, the impact it may have on employment in the long term and the industrial competition on a worldwide scale.
   Such a common European strategy is also needed in view of the considerable funds which are required and which may be as high as 1000-1500 MECU for the next ten years. This is beyond the possibilities for individual industrial and national programmes. It would also be a powerful instrument to bring together the many dispersed competences and disciplines required for fuel cell development, thus avoiding overlap of activities and allowing an efficient use of available resources.

9. The main goal of this common strategy is a rapid commercialization of affordable and competitive European fuel cell technologies. Key elements are here emphasis on low cost stacks and simplification of systems. The cost target for 2005 is an installed system cost of approx. 1500 ECU/kW and a lifetime of up to 40.000 hours.

10. The general strategy for the next ten years is based on the following elements:
    - Emphasis on low cost low temperature fuel cell stacks which in the medium term may be commercialized for applications in buildings and transport;
    - Simplification of systems by developing the concept of fuel cell networks and of fuel cell systems without external reformers;
    - Continuation of R,D&D on high temperature fuel cells for industrial cogeneration and large scale electricity production in the long term.

In general, the development of fuel cells should emphasize fuel cell systems for applications in cogeneration and transport. In addition, the size of the stacks and stand-alone systems should be in the range of approximately 200-300 kW.

11. **Emphasis on low cost low temperature fuel cell stacks.** To achieve a low cost, the development of solid polymer fuel cells (SPFC) operating at 80 to 130°C is preferred, both for stationary and transport applications. The higher current density and low temperature manufacturing technologies of SPFC can lead to a stack cost as low as 200 ECU/kW in the long term (i.e. 2-3 times lower than for high temperature fuel cells). Due to this low cost SPFC is likely to be the only fuel cell type which may be economically feasible in transport applications. Waste heat offered by SPFC will be around 80°C and can be used for buildings cogeneration. It is the aim to come to a to first commercialization of SPFC for cogeneration applications in buildings in 5 to 7 years and for transportation at a later stage.

12. **Simplification of systems – fuel cell networks.** Presently, fuel cell systems include components such as a reformer, purification equipment and a fuel cell stack. A part of the system, such as the reformer and the purification equipment, has an

economy of scale and another part, the fuel cell stack, is modular. In the case of SPFC, which are most promising at 20-200 kW scale, the advantage of very low cost stacks is offset by the high cost of reformers which are very expensive for this size.

The concept of a fuel cell network is proposed to simplify the system and to reduce the cost. It consists of a central fuel processor (reformer and purification) producing pure hydrogen which will feed a network of pipelines to fuel cell stacks near users. The stack duty is optimized for production of heat and electricity. The hydrogen from the fuel processor can also be used for fuel cell driven buses in public transport. This concept could lead to fast commercialization because:

- The reformer and purification equipment are commercially available and have a low cost per kW at a 2-5 MW scale.
- The technology and cost of the hydrogen pipeline network are similar to natural gas network.
- The 200-300 kW fuel cell stacks are modular and can be cheaply mass produced. The use of pure hydrogen will increase the current density which would lead to additional cost reduction.
- High overall efficiency is expected from cogeneration as well as from transport applications. Pollution levels will be 10 to 1000 times lower than in conventional systems.

Beside this network concept, another path for system simplification is the development of systems which do not require external reformers, such internal reforming MCFC and SOFC and direct methanol fuel cells (DMFC).

13. **Continuation of R,D&D on high temperature fuel cells** for industrial cogeneration and large scale electricity production in the long term. Heat for industrial processes ranges from 100°C to 1500°C. High temperature fuel cells can provide a large part (200 C-900 C) by means of cogeneration with MCFC and SOFC. With higher efficiency in electricity production, MCFC and SOFC may also be more suitable for large scale (MW size) electricity production than SPFC. Commercialization of MCFC and SOFC may be expected in 10 to 15 years. The first market opportunities are simple fuel cells for use with pure hydrogen or syn gas from coal or biomass gasifiers to be used in the networks described above. Internal reforming SOFC and MCFC still require much R,D&D to solve a number of technical problems and are a longer term option.

14. In general, fuel cells for **cogeneration in buildings and industry will be emphasized**, in view of increased emphasis by regulations and legislation on combined production of heat and power. The size of the fuel cell stacks and stand-alone systems will be limited in size up to approx. **200-300 kW**. At this scale, conventional gas turbines yield a low efficiency and are very expensive, while Diesel engines cause pollution emissions 3 to 4 orders of magnitude higher than fuel cells and are not suitable in urban areas. Small fuel cell systems up to 200-300 kW have the additional advantage that the cost of demonstrating reliable operation for 40.000 hours is within acceptable limits.

RESEARCH, TECHNOLOGICAL DEVELOPMENT AND DEMONSTRATION TASKS

15. **Low cost fuel cell stacks**: development of SPFC and strongly related DMFC for cogeneration in buildings and transportation, aiming at a first commercialization in 5 to 7 years.

Research and development

- Development of more advanced SPFC and DMFC systems to increase the efficiency and reduce the cost (e.g. SPFC at 130°C and operation at 1 bar etc). This work will include the development of cost-effective and compact methanol and natural gas reformers.
- Development of fuel cell driven vehicles, in particular buses for public urban transportation.
- Development of cheap manufacturing methods for simple SPFC of up to 100 kW using hydrogen and air.

Demonstration of isolated applications to quantify potentialities of the technologies.

16. **Systems simplification – urban fuel cells network:**

Research and development:

- Feasibility study to identify the best structure, application and location for a fuel cell network with a large central reformer and SPFC stacks for cogeneration in buildings and fuel cell driven buses for public transport.

For Demonstration:

- Installation and operation of the above network. Other fuel cell types such as MCFC may also be included.

17. Development of **high temperature fuel cells** (MCFC and SOFC) for industrial cogeneration, aiming at a first commercialization in 10 to 15 years.

For research and development:

- Development of simple, modular and low cost fuel cell systems without an external reformer such as IR-MCFC and IR-SOFC using natural gas. This should include the development of system simulation models and balance of plant (BOP) lifetime tests with all auxiliary components and a simulated fuel cell stack.
- Feasibility study to identify the best structure, field of application and location for a high temperature fuel cell network for industrial cogeneration.
- Development of cheap production methods for simple up to 100 kW MCFC (1 bar) and SOFC stacks and components to be used in industrial fuel cell networks, using pure hydrogen or syngas.

Demonstration:

- Installation and operation of the fuel cell network for industrial cogeneration using coal or biogas gasifier and MCFC or SOFC stacks up to 300 kW. PAFC could also be considered if they are cost competitive.
- Improvement of components manufacturing and new production methods.

18. **Development of fuel processors** for the production of hydrogen from natural gas and methanol and the **development of cheap and efficient electrolysers** for the production of hydrogen by electrolysis of water with renewable or nuclear electricity, based on reversed SOFC and SPFC technology.

19. The above fuel cell R,D&D programme for ten years is proposed by the European Commission. It should be carried out in close collaboration between different services in the Commission and the programmes involved are NNE (JOULE and THERMIE) and IMT. This collaborative action will serve as a catalyst and nucleus for a closer collaboration between EU, national and industrial programmes in Europe.

20. The proposed global strategy is summarized in the following table:

	PAFC	*MCFC*	*SOFC*	*SPFC*	*Auxiliary*
Present state	3000 ECU/kW (system) 1 MW EU - 11MW Japan	20.000 ECU/kW (stack) 100 kW	30.000 ECU/kW (stack) 25 kW	5.000 ECU/kW (stack) 50 k	
2005 GOAL	stack < 300 ECU/kW and system < 1000 ECU/ kW 40.000 hours	500 ECU/kW (stack) and 1500 ECU/kW(system) 40.000 hours	500 ECU/kW (stack) and 1500 ECU/kW (system) 40.000 hours	200 ECU/kW (stack) and 1500 ECU/kW (station. system) 20.000 hours (stationary)	
RTD activities	none	a) Corrosion, life improvement and cost reduction (year 0-5) b) Manufacturing of simple MCFC stacks (yr 3-6) c) Internal reforming MCFC and balance-of-plant (yr 0-10) d) Feasibility study high temp.5-10 MW network (yr 0-2)	a) Material research and cost reduction (lower temp., increase cell surface) (yr 0-10). b) Internal reforming and BOP (yr 0-10) c) Manufacturing of simple stacks (yr 3-6). d) Feasibility study 5-10 MW (see MCFC)	a) Development of advanced SPFC (yr 0-10) b) Development of FC driven electric vehicles (yr 0-4) c) Manufacturing of simple SPFC (yr 0-3) d) Feasibility of 2-5 MW network (yr 0-2)	cheap and compact reformers for stationary and transport applications
Indicative budget (total = 85 mecu)	0%	29	29	35%	7%
Demonstration	a) Demonstration of a 5-10 MW network (yr 3- 10) b) Improvement of components production (yr 0- 5) c) Support to some uses if they reach a threshold cost (yr 0-5)	a) Demonstration of a 5-10 MW network (yr 3-10) b) Support to some applications if positive results from current projects (yr 3-10) c) Improvement of components production. (yr 5-10)	a) Demonstration of a 5-10 MW network (yr3-10) b) Support to some initiatives, especially for IR- SOFC (yr 7-10)	a) Demonstration of a 2-5 MW urban network (yr 3-10) b) Experience in transport applications (yr 5- 10) c) Experience in building with cold production (yr3-10)	Improvement of ancillary equipments (ex: turbo-compressors, filters, fuel gas cleaning devices, inverters)
Indicative budget (total = 75 mecu)[1]					

[1] Distribution will be fixed according to the results of the R&D activities.

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INTRODUCTION

Since 1986, the EU is carrying out R,D&D in the field of fuel cells, these activities were predominantly of a R&D nature, with an emphasis on basic material research and the development of cells and stacks. With fuel cells coming closer to the market EU demonstration activities have started since several years.

The aim of this document is to assess the present state of the art of fuel cells and define a common EU R,D&D strategy which integrates the efforts within the EC, in particular in DG XII (Research, Science and Education) and DG XVII (Energy) and which is well coordinated with national and industrial fuel cell programmes of EU Member States. This strategy has a time horizon of 10 years and should therefore be a guideline for fuel cell R,D&D in the 4th and 5th Framework Programmes.

WHY A COMMON EUROPEAN STRATEGY FOR FUEL CELLS

Fuel cells are electrochemical electricity generators which can produce electricity with a high efficiency and heat at temperatures which ranges from 80 to 1000°C. With fuels such as oil, coal and natural gas the pollutant emission levels are 10 to 1000 times lower than in conventional energy conversion systems; depending on the type of application. Due to the high efficiency, the CO_2 emissions will be 30 to 50% lower than in conventional systems. With hydrogen as a fuel the pollutant emission is zero as only water is formed. Fuel cells can be used in a large range of applications in all the demand sectors and are expected to make a major contribution to pollution abatement. Fuel cells are presently too expensive and their reliability still has to be demonstrated. Free market forces will not be sufficient to bring about a break through for fuel cells due to the high cost and the fact that existing technologies have had many years of development to reduce the cost, develop cheap mass production methods, etc; fuel cells are only at the beginning of that process. There are no strong incentives for industry to invest in this new technology. Short and medium term profits are the driving market mechanisms and not energy efficiency and pollution abatement; industry is reluctant to make large investments in high risk options where they can only expect profits in the long term.

Public funding is therefore needed to support industry in an effort to bring about a break through for this environmentally friendly technology. A coordinated European activity in this field is highly desirable for the following reasons:

- The required funding for a long term programme leading to the production of fuel cell power plants and road traction systems is large and beyond the reach of single European companies and national programmes.
- Fuel cell development requires multidisciplinary R, D &D involving technological competence which are widely dispersed in Europe. A European R, D and D programme is the most efficient way of bringing these technologies together.
- Existing fuel cell research in national and industrial programmes in Europe is already well coordinated through fuel cell R,D&D programmes of the Commission. A number of EC projects are being carried out in which most of the companies and utilities, involved in fuel cell activities, participate.

- Fuel cell research is in agreement with the Commissions' objectives for rational use of energy, reduction of the emission of CO_2 and other pollutants and increased competitiveness of European industry.

FUEL CELLS: CLEAN ENERGY CONVERSION FOR ALL DEMAND SECTORS

At present combustion processes are used for around 85% of the energy conversion in Europe. Much progress is made in improving both their efficiency and pollutant emissions. However the efficiency of combustion systems is limited by the Carnot efficiency and it will be difficult for combustion systems to satisfy future requirements which will be set by increasingly severe environmental legislation.

Fuel cells are electrochemical electricity generators which can produce electricity with an efficiency of 60-65%; they are not limited by the Carnot efficiency. They can also be used for simultaneous heat/power generation where they can produce heat between 80 and 900°C, depending on the fuel cell type. This makes them suitable for cogeneration both in the building and industrial sector. For applications in the transportation sector fuel cells are expected to bring about efficiencies which are 2 times higher than with conventional internal combustion engines. Like in combustion systems, fuel cells can use oil, natural gas, coal and methanol. These fuels however have to be converted into hydrogen with reformers or coal gasifiers, as fuel cells generally require hydrogen as a fuel. In case hydrogen will be used as an energy vector in the long term, fuel cells will be even more attractive in terms of cost and efficiency.

The major advantage of fuel cells is their low pollutant emission. If hydrogen is used only water is formed. In case fossil fuels are used, pollutant emissions in fuel cells are 10 to 100 times lower than in conventional systems in stationary electricity production and cogeneration. In transportation fuel cells, using fuels such as methanol, give a 100 to 1000 times lower pollution than petrol or Diesel engines.

Fuel cells like combustion systems, are very versatile and can be used between 10 kW and 100 MW. As compared to combustion systems fuel cells have two advantages: a high efficiency, also when units are small (this contrary to for example petrol engines); the part load efficiency is high and can be even higher than full load efficiency (with combustion systems the part load efficiency is mostly considerable lower than at full load).

FUEL CELLS IN A RENEWABLE ENERGY STRATEGY

In the 4th Framework Programme renewable energy is strongly emphasized. The long term objective is to cover a large part of the future energy requirements with renewable energy. Together with nuclear energy this could lead to clean energy conversion and utilization. However the structure of both energy production and utilization will have to be very different from the present system where electricity production consumes only 30% of the primary energy and is strongly centralized.

In a renewable/ nuclear energy scenario, energy will be predominantly produced as electricity (nuclear energy is only produced as electricity and also most of the renewable energy technologies such as hydropower, wind, photovoltaic and a large part of biomass and geothermal energy, generate electricity) This would have to lead to a strong change in the energy utilization pattern. Electricity utilization in the demand sectors (which now forms only 30% of the primary energy) would have to increase considerably and technologies such as electric heatpumps, electric battery driven vehicles are likely to be strongly promoted. In such a clean energy scenario **energy vectors** remain indispensable for the production of heat and road traction, which presently form 70% of the primary energy utilization.

In addition renewable electricity will be produced in a dispersed way and will not always be at the place where it will be used. Also for this reason energy vectors will be needed to adapt the supply to the demand.

Hydrogen is here the most likely candidate as an energy vector: it can be used in a clean way and can also be produced without pollution by electrolysis of water with renewable or nuclear electricity. The production of fuels from biomass is another possibility. A promising route for electricity production is the gasification of biomass into a hydrogen rich gas which is used as a fuel in a gas turbine or fuel cell to produce electricity. This hydrogen rich gas can also be used as an energy vector for energy production elsewhere.

If hydrogen is used as energy vector, fuel cells are by far the most suitable energy conversion system in particular as compared to combustion systems: they have zero pollutant emission, high energy conversion efficiency for electricity production and can provide heat by cogeneration both for buildings and a large part of the industrial sector.

Development of cheap and efficient electrolysers is a key issue in renewable energy scenarios. A fuel cell is a reversed electrolyser and much of the R&D results obtained for fuel cells can also be used for electrolysers. Development of a high temperature electrolyser (a reversed solid oxide fuel cell) could benefit much from SOFC research; such electrolysers are expected to lead to electricity savings of 30-40%. Development of solid polymer electrolysers (a reversed solid polymer fuel cell) could lead to a strong cost reduction of electrolysers. This would allow the use of small electrolysers for domestic applications and small commercial units.

Although such renewable/ hydrogen concepts seem remote they are already explored by several projects such as the Euro-Quebec project and the Japanese WE-NET project which both aim at the clean production of hydrogen by electrolysis of water with hydropower in remote areas and at transportation to industrialized countries where it could provide clean utilization of energy. The Euro Quebec project spent 20 MECU during the last three years and WE NET allocated 60 MECU for the period 1993-1995 and plans to spend 2000 MECU in the next 25 years.

FUEL CELL TYPES AND THEIR STATE OF THE ART

Different types of fuel cell exist. They operate at temperatures ranging from 80°C to 1000°C producing electricity with a high efficiency and waste heat at a temperature somewhat lower than the operating temperature. The state of the art of these fuel cell types is very different.

The first generation **phosphoric acid fuel cells (PAFC)** which operate at 200°C, are most close to the market. They are mainly envisaged for stationary applications. At present PAFC plants in operation range from 5 kW to 11 MW and they play an important role as a market opener for the fuel cell technology. The efficiency for electricity production of PAFC plants is around 40%; their pollution levels are 10 to 100 times lower than conventional gas turbines and Diesel engines. Most of the PAFC plants are used for cogeneration in buildings; in view of their relatively low operating temperatures they are less suitable for cogeneration in industry. Due to their high cost PAFC can only achieve acceptable payback times when they operate continuously, preferably at full load; this requires a lifetime of at least 40.000 hours. At present PAFC systems have been operational for 15.000 to 20.000 hours and the main technical problem is to develop PAFC systems with a reliable operation during 40.000 hours. PAFC prototypes are manufactured by 8 Japanese and 2 US manufacturers. Although PAFC are not produced in Europe, European companies are world leaders in the manufacturing of auxiliary equipment such as reformers and DC - AC inverters. It is expected that PAFC will find first commercial applications in 3 to 5 years; Japanese MITI is planning 2000 MW of PAFC in 2000 and 8000 MW in 2010. In Europe 15 PAFC plants are presently in operation; they range from 50 to 200 kW. A 1.3 MW PAFC plant with US fuel cell stacks and a European reformer and power conditioning system is in the start-up phase in Milano, Italy.

Second generation **molten carbonate (MCFC) and solid oxide fuel cells (SOFC)** can reach efficiencies of 60-65 % for electricity production and have very low pollution levels. They are mainly envisaged for stationary MW size electricity production, for cogeneration, for trains and for ships; oil, coal or natural gas can be used as fuels. They operate at 650 and 1000°C respectively and have the advantage that high temperature waste heat can be used for industrial processes or for additional electricity production. Industrial cogeneration is thus possible with MCFC and SOFC; this contrary to PAFC, where cogeneration is mainly limited to the building sector. The high temperature operation of MCFC and SOFC has another major advantage as compared to PAFC: the possibility for internal reforming of natural gas in the fuel cell. Natural gas is here transformed into hydrogen in the fuel cell using its waste heat. IR-MCFC and IR-SOFC are strongly simplified systems as an external reformer is not needed; this leads to considerable cost reductions and an improvement of the efficiency as compared to fuel cells with external reformers such as ER-MCFC, ER-SOFC and PAFC (PAFC operating at 200°C is not suitable for natural gas reforming which requires temperatures of at least 600°C). In Japan and the US, prototype MCFC plants of 100 kW have been constructed as a first stage to MW size plants; 25 kW SOFC plants have been constructed in the US. In Europe 100 kW MCFC and 20 kW SOFC plants are presently being developed. Both SOFC and MCFC still have a number of technical problems which will be discussed below and which require a major R,D&D effort; also here the objective is to achieve a lifetime of 40.000 hours. This lifetime requirement is an important cause of the slow progress of PAFC, MCFC and SOFC development, as it requires time consuming and costly lifetime tests with a large number of full size fuel cell systems, to guarantee their reliability.

Alkaline (AFC) and solid polymer fuel cells (SPFC) operate at typically 80°C using hydrogen, methanol or natural gas as a fuel; AFC has a liquid or a matrix type alkaline electrolyte and SPFC a solid polymer electrolyte. They are mainly foreseen for transportation applications and are 2 times more efficient than petrol engines. The emission of CO_2 is strongly reduced as it is inverse proportional to the efficiency. The pollutant emission of fuel cells is zero with hydrogen; with methanol the pollutant emission is 100 to 1000 times lower than in petrol engines. The use of AFC is mainly limited to pure hydrogen; the use of hydrogen produced by reformers causes problems due to the fact that CO and CO_2 in the reformer gases impair the operation of the alkaline fuel cell. AFC have been used extensively in space craft but are of limited interest for terrestrial applications. SPFC stacks have a strong potential for cost reduction and could in the long term achieve a cost as low as 200 ECU/kW. They may, possibly together with hydrogen fueled AFC, be the only fuel cell type which can be made cheap enough to be competitive in transport applications. Transportation has the advantage that operational lifetimes of only 5000 hours are required. This could lead to a much faster progress in R,D&D as compared with fuel cells for stationary applications which require 40.000 hours. If the ambitious cost targets for transportation can be achieved, SPFC will almost certainly also be of interest for small scale stationary applications for electricity production, even although their efficiency with natural gas using a reformer is not expected to be much higher than 40%. The technical feasibility of AFC and SPFC driven buses using hydrogen, has recently been demonstrated. A major R,D&D effort however is needed to reduce the cost. Major efforts on SPFC are going on in Europe, Canada, Japan and the US. A very promising type of SPFC is the direct methanol fuel cell (DMFC), which oxidizes methanol directly and does not require a reformer. Like in IR-MCFC and IR-SOFC this will lead to a strongly simplified system and to a large cost reduction. DMFC are particularly interesting for road traction. Promising results have recently been obtained, but much research is still needed.

A factor which strongly influences the cost of the fuel cell stack is the current density (the current per cm^2 cell surface). With a ten times higher current density, the required cell surface for 1 kW is ten times smaller; high current densities therefore lead to a low material and production cost per kW. The values for the current density with a cell voltage of 0.7 V, for the different fuel cell types with natural gas as a fuel and air as the oxidant, have been given below. With 0.15 A/cm^2 MCFC has a low current density. Both PAFC and SOFC have current densities of around 0.3 A/cm^2; SOFC however has still a strong potential for improvement. AFC and SPFC achieve current densities of 1 to 2 A/cm^2 with hydrogen as a fuel. With natural gas and a reformer, SPFC achieve typical current densities of 1 A/cm^2; in particular SPFC therefore has a strong potential for cost reduction. With DMFC using methanol 0.4 A/cm^2 has been obtained with 0.5 V.

Another factor which influences the field of applications is the time required to bring the fuel cell from room temperature to the operating temperature (cold start up time). For MCFC and SOFC the cold start up time is around 10 hours, for PAFC 4 hours and for AFC and SPFC a few minutes. All fuel cell types can change their load rapidly once they have reached their operating temperature. PAFC, MCFC and

SOFC have to be kept at their operating temperature and should preferably be used for applications which require many operational hours per year. AFC and SPFC are, due to their very short cold start up time, suitable for applications where the fuel cell is used occasionally eg. transportation.

POSSIBLE MARKETS FOR FUEL CELLS.

Fuel cells are envisaged for applications in a range from 10 kW to 100 MW and will come in competition with currently used systems such as gas turbines, steam turbines, combined cycles, Diesel engines for stationary electricity production and petrol and Diesel engines for road traction.

Stationary electricity production

At present electricity production is largely centralized and produced with plants of typically several hundreds of MW. In view of the present state of the art of fuel cells, it is unlikely that this market can be addressed within the next 10 years. Moreover it is here where conventional technologies can best compete with new fuel cell technologies due to: a low cost per kW for large installations caused by a strong economy of scale; a high efficiency due to the combination of different technologies (eg combined -gas and steam turbine-cycle, coal gasification combined cycle etc.). In the long term however fuel cells may play an important role as a component in such combined systems together with conventional gas and steam turbines. The combination of coal gasifiers with SOFC and a combined cycle or MCFC with steam turbines is expected to lead to strongly improved efficiencies.

An increasing part of the electricity production however is produced by decentralized and smaller electricity plants which are located close to the user. This tendency towards decentralized electricity production is caused by: the high cost and energy losses of electricity transport and distribution, in particular over long distances, and to remote areas; an increasing resistance of the public against installation of high tension lines for environmental and aesthetic reasons.

This tendency towards decentralized electricity production in Europe is reinforced by an increasing number of regulations which require the use of waste heat produced during electricity production. This in order to improve the overall efficiency of electricity and heat production and to reduce overall pollutant and CO_2 emissions. Another important development is the increased possibility for small electricity producers, to get free access to transmission lines. Fuel cells can play a major role in increased decentralized electricity production due to:

- Low pollutant emission and low noise levels which allows location in populated areas. The NO_x emission of gas turbines and Diesel engines is typically 10 and 100 times higher respectively than in fuel cells. This makes combustion systems less attractive for location in urban areas;
- Modularity which allows an optimum adaptation to the energy use requirements and cheap mass production;
- Fuel cells such as MCFC and SOFC produce high temperature waste heat and are suitable for cogeneration in both buildings and industry;

- Low maintenance cost due to low number of moving parts and to autonomous operation.

Of the different fuel cell types **PAFC and SPFC are likely to have the best market opportunities in the next 10 years**; they are most close to the market but are only suitable for cogeneration applications in buildings due to their low temperature waste heat. MCFC and SOFC allow cogeneration applications for both buildings and industry. These high temperature fuel cells however still require much R&D to solve a number of technical problems and to reduce the cost to acceptable levels; their commercialization may take more than 10 years.

The upper level of the allowable cost of fuel cell plants for cogeneration applications lies around 1500 ECU/kW. The manufacturing cost of PAFC may come down to this level within a few years. In Japan 2000 MW and 8300 MW of PAFC are planned in 2000 and 2010 respectively; MITI has an active policy in promoting the installation of PAFC plants by contributing 30% of the cost. Due to their high investment cost PAFC are expected to be economically feasible with lifetimes of the order of 40.000 hours. This lifetime has not yet been demonstrated and the guarantee for reliable operation for 40.000 hours is at present the major technical barrier for the market introduction of PAFC. Due to the economy of scale of several system components such as the reformer and purification equipment, only systems larger than 200 kW are likely to be economically attractive.

The SPFC is complementary to the PAFC in that its application is expected to lie between 10 and 200 kW. It differs from PAFC in a number of ways which will strongly influence its market potential. The cold start up time of SPFC is only a few minutes (the cold start up time of PAFC is 4 hours) and even at room temperature SPFC have already 80% of their rated power at the normal operation temperature. Due to a high current density and a potential for cheap manufacturing, SPFC stacks are expected to become cheap. The low cost and the short cold start up time could make SPFC attractive for applications where they operate only during a relatively small number of hours per year. Lifetimes much shorter than 40.000 hours are then allowed to achieve acceptable payback times; this could accelerate R,D&D of SPFC considerably.

Finally the low operating temperature of SPFC makes the integration with a reformer less interesting. This contrary to higher temperature fuel cells where waste heat can be used in the reformer and where integration and optimization of the complete system is indispensable. For SPFC a concept could be envisaged for domestic and commercial applications where the reformer and the stack are optimized separately. Such a separation has the advantage that one deals with relatively simple systems which decreases the cost and improves the reliability; moreover reformers, optimized for hydrogen production from natural gas, are already commercially available. The main R,D&D effort should have to be focussed on the development of cheap SPFC stacks. These and other concepts should investigated with computer simulation studies.

Transportation

Presently road traction consists predominantly of petrol and Diesel engines. The transportation sector consumes around 20% of the overall primary energy but causes in Europe 68% of the overall NO_x emission and a major part of the CO, HC and particulate emissions, which is largely concentrated in urban areas. The fuel cell driven electric vehicle has a zero pollutant emission when hydrogen is used as a fuel and a 100 to 1000 times lower pollutant emission as compared to petrol engines, with methanol; fuel cells are therefore an important option for clean transportation. Fuel cells have the advantage that they can give vehicles a range which is comparable with internal combustion engine (ICE) driven cars. This contrary to battery driven vehicles which in the medium and long term may be expected to have a range of 150-200 km. Fuel cells have energy efficiencies which are 2 times higher than petrol engines which can lead to a strong reduction in CO_2 emissions. Development of cost-effective fuel cells for road traction could therefore make a major contribution to zero and low emission vehicles. Due to the low cost of presently used petrol and Diesel engines, cost reduction is the major objective of R,D&D. SPFC is the fuel cell type which has the best chance to achieve the required cost targets of 100-200 ECU/kW. The potential for cost reduction, its short cold start up time of a few minutes, the fact that it has already 80% of its rated power at room temperature and the high power densities of 1 kW/liter make SPFC the most suitable fuel cell type for road traction applications. The use of hydrogen as a fuel leads to a simple and compact system with few components.

FUEL CELL ACTIVITIES IN EUROPE

Fuel cell development in Europe started in the sixties when a number of large fuel cell programmes started in the Netherlands (MCFC), Germany (SOFC) and Belgium, France and Germany (AFC). All these activities, with the exception of AFC in Belgium and Germany were stopped around 1976. Interest in fuel cells was revived in 1985. At that time Europe was lagging far behind the US and Japan, where large fuel cell R&D programmes had been going on for 20 years. EC fuel cell research in JOULE, which started in 1985, played a major role in triggering interest for fuel cells in Europe. Following the EC, national FC R&D programmes initiated in the Netherlands (1986), Italy (1987), Spain (1989) and industrial programmes started from 1988. At present Europe is well placed in small scale fuel cell development (e.g. for road traction) but needs to make progress in large scale applications where the US and Japan are strong and Europe is lagging 3 to 4 years behind. EC research at present is well coordinated with European national and industrial fuel cell R&D programmes. Total funding for fuel cell R,D&D from both public authorities and industry funds is estimated to be around 70 MECU per year.

Fuel cell activities within the EC

Fuel cell R,D&D in the EC is presently carried out in different programmes: JOULE and BRITE in DG XII and THERMIE in DG XVII. Fuel cell activities in these three programmes are complementary. JOULE focusses on basic research and on stack and system development with the aim to demonstrate their technical feasibility. BRITE deals with the development of production processes for systems and materials. THERMIE allocates funds for the demonstration of the economic feasibility of new technologies. In the period 1992 to 1994 the overall EC contribution to fuel cell R,D&D amounted to around 32 MECU. As the EC generally contributes around 50% of the total cost of projects , the total cost of this research amounts to around 64 MECU.

In JOULE during the period 1992-1994 around 23 MECU is allocated to 22 projects. JOULE focusses on MCFC and SOFC where basic research was carried out to improve the lifetime (corrosion problems) and reduce the cost. In addition a series of projects aimed at scaling up MCFC and SOFC stacks; starting with small cells in 1985 this research led to ongoing projects which develop ER-MCFC stacks of 100 kW, IR-MCFC of 10 kW and SOFC of 20 kW.

In 1993 JOULE changed the emphasis from basic research and stack development to prototype and systems development. This led to projects with first generation PAFC and balance of plant (BOP) projects for SOFC and MCFC. PAFC are expected to be commercial in 3 to 5 years and are believed to be very important as a market opener for second generation MCFC and SOFC, in which European manufacturers are strongly involved.

For transportation applications SPFC, DMFC and natural gas and methanol reformers are being developed. Two projects are aimed at the development of systems: two car manufacturers are developing a fuel cell driven passenger car which uses hydrogen as a fuel; in a stationary test facility components such as fuel cells, reformers etc. are integrated in a 5 ton van driven by fuel cells which use methanol as a fuel.

In the BRITE programme around 7 MECU is allocated to five projects in the field of SOFC.

In THERMIE six projects are carried out on PAFC and MCFC with a total EC contribution of 7.3 MECU.

Fuel cell R,D&D in Europe is carried out in different national, industrial and EC programmes. Although EC funding for fuel cell R,D&D in Europe forms only a relatively small part of the overall fuel cell funding, EC programmes play an important role in bringing about a collaboration and information exchange between most of the fuel cell programmes in Europe. Due to the condition that a project should have several partners from different EC Member States, each EC project on the average consists of three to four partners and in the 35 ongoing EC fuel cell projects around 100 organizations participate which are also involved in national and industrial fuel cell activities. Regular EC fuel cell contractor meetings assure a continuous contact and information exchange between major fuel cell groups in Europe.

European national and industrial programmes.

Fuel cell R,D&D in Europe is carried out in national, industrial and EC programmes which are strongly interconnected: organizations from different countries often participate in the same project and funding for a project may come from national, industrial and EC sources. Due to this strong interconnection a description of European fuel cell activities per country is not very practical. After a short overview with priorities and funding levels in national programmes, an overview of European fuel cell activities will therefore be given per fuel cell type.

In the **German national fuel cell programme** SOFC is presently emphasized. The budget of the German fuel cell programme in 1992 was around 5 million $. A four year fuel cell programme is planned which will be focussed on SOFC and SPFC. The total budget is likely to be around 30 MECU of which 50% will be funded by industry. Since 1986 fuel cell efforts in the **Netherlands** are predominantly focussed on the development of ER and IR MCFC; the available budget for a period of 5 years 1992-1996 amounts to 40 MECU; the Dutch government and utilities contribute financially to this project. In **Spain** a 15 MECU 5 year programme is carried out by Spanish utilities for the development of MCFC. In **Italy** fuel cell R,D&D is carried out since 1987; the present budget amounts to 40 MECU for a period of 3 years (1994-1996); both government and industry contribute to this programme. The main effort is here directed towards the development of a 1 MW PAFC plant ; also work on MCFC and SPFC receives considerable funding. **Denmark's** national programme aims at establishing technologies to make planar stacks, spending 14 MECU for the 1993- 1996 period. Since 1992 the **UK** government started a fuel cell programme which focusses on SOFC and SPFC; public funding amounts to around 2 MECU per year. Apart from the fuel cell activities in the European Community research is carried out on SOFC in **Norway and Switzerland**.

PAFC

In Italy a 1 MW PAFC plant is being developed, which includes two 675 kW PAFC stacks produced by the US company IFC; other equipment was delivered by European companies (eg. Ansaldo Ricerche in Italy developed power conditioning and control systems, Haldor Topsoe in Denmark developed the reformer). This plant is expected to be operational in 1994. Around fourteen 50 to 200 kW prototype PAFC cogeneration plants produced by US and Japanese manufacturers have been installed in different European countries, mainly with utilities, to get experience with fuel cell electricity generation.

MCFC

Presently three large projects exist in Europe: A large industrial programme amounting to 75 MECU for a period of 9 years is carried out by a consortium consisting of MTU (D) and Haldor Topsoe (DK) and the utilities RWE (D), Ruhrgas (D) and Elkraft (DK). This project is aimed at the development of MCFC and is carried out in close collaboration with the US company ERC.

In the Netherlands another MCFC project is funded with a budget of 40 MECU for a five year period. The ECN research establishment played a crucial role in this development. With MCFC coming closer to the market, an industrial joint venture BCN was set up by the companies Stork and De Schelde for further development and commercialization of MCFC. A first target is the development of a 250 kW ER-MCFC for natural gas and a 250 kW MCFC for coal gas from a coal gasifier; both systems are expected to be operational in 1995.

In an third industrial MCFC project "MOLCARE", Ansaldo is developing a 100 kW MCFC plant in collaboration with TGI(ES) and ENEA(IT) and the Utilities Iberdrola(ES), ENEL/CISE(I). In addition to industrial funds, this programme is supported by THERMIE and the Italian and Spanish governments.

SOFC

A project carried out since 1992 by Siemens-D, ECN-NL and Imp. College and GEC from the UK is developing a flat plate SOFC with metallic bipolar plates and with a multiple cell array. A 1kW SOFC stack with multiple array cells has been successfully tested. Work on the development of a 20 kW SOFC plant, which is expected to be operational in 1995, is presently going on. The funding for this project is estimated to be around 20 MECU of which 50% is paid by the EC.

A second project carried out by British Gas, ICE (UK), Riso (D) and TNO (NL) is aiming at a 1 kW SOFC with a structure which is a mixture of tubular and flat plate concepts. This project receives funding from the EC and the UK government.

Research is also carried out on the development of a flat plate SOFC unit with ceramic bipolar plates. This project aims at kW size SOFC units. Dornier (D) is carrying out this research and receives funding from the German government and the EC; Cookson (UK) participates in this project.

Two collaborative EC projects deal with SOFC material research. The main objective is the development of new materials in particular electrodes which will allow the operation of SOFC at 850°C instead of the present operating temperature of 1000°C. This is expected to lead to a strong cost reduction due to the fact that at 850°C less costly materials can be used for auxiliary equipment such as heat exchangers, piping, etc. These basic material research projects are carried out by Ris , Denmark with 6 partners and INPG, France with 4 partners.

A Danish SOFC project with 7 MECU for 1990-1992 is developing technical know-how on the manufacturing of cells and stacks (bipolar flat plate). In addition basic materials research is carried out to improve SOFC components

In Switzerland the original HEXIS concept is being developed by Sulzer; a 1kW SOFC stack is expected to be operational in 1993.

In Norway two major programmes exist for the development of flat plate SOFC. A project of Statoil (1993-1995), with a budget of 3 million $ per year, is aiming at a 5-10 kW planar SOFC plant in 1995. In another collaborative project five Norwegian groups are carrying out a 3 year research programme (1991-1994) which should lead to a 3-4 kW unit in 1994. For this programme around 7 million $ is available for the three year period.

SPFC

The development of SPFC gained a strong interest in Europe; the major companies involved in this development are Siemens, DB (D), VSEL, Johnson Matthey (UK) and De Nora(I). In the past Siemens developed SPFC for military applications and is presently involved in SPFC development for transportation applications aiming at cost reduction. In March 1993 Daimler Benz entered into a joint R&D programme for the development of SPFC with the Canadian company Ballard, which is world leader in this field. DB is contributing 13 MECU in this common research project which is to last 4 years. VSEL (UK) also has an agreement with Ballard and is developing SPFC systems both for transport and stationary applications. Johnson Matthey is world leader in electrode and catalyst development. De Nora (I) is developing 40 kW and 30 kW SPFC stacks for a SPFC driven bus (Ansaldo,It) and passenger car (Renault,F) respectively with funds of the EC; SPFC activities of a more basic nature are going on in France. The development of DMFC, carried out by a number of organizations in Denmark, France, germany, Ireland and the UK, is also mainly funded by the EC. The DMFC is a special type of SPFC, which oxidizes methanol directly and does not need a reformer.

A non-exhaustive list of main actors from industry and utilities in the field of fuel cells in the EU is given below:

High temperature fuel cells (PAFC, MCFC, SOFC): MBB, MTU, Siemens (D); Haldor Topsøe (D); TGI (E); Ansaldo, ENEA, ENI (I); GEC, ICI, Rolls Royce (UK); ECN, De Schelde, Stork (NL) and the following utilities, British Gas, Ruhrgas, RWE (D), Elsam (DK), ENEL, AEM (I), Iberdrola (E), SEP (NL).

Low temperature fuel cells (AFC, SPFC, DMFC): Elenco, Hydrogen Systems (B); Dornier, Siemens (D); De Nora, Ansaldo, Fiat (I); IFP(F); Johnson Matthey, VSEL (UK).

Reformers: Both Haldor Topsoe (DK) and KTI-MAN (NL,D) are a world leaders in the development of methane reformers for different types of fuel cells. Other European companies involved in the development of methane and methanol reformers are Rolls Royce, CJTB (UK), Ansaldo, Technars (I).

FUEL CELL ACTIVITIES IN JAPAN AND THE US

Japan

Fuel cell R,D&D in Japan has been going on for many years with a strong support from the Japanese government. At present public funding for fuel cell R,D&D amounts to 35 MECU per year; it is estimated that industry contributes an additional 100 MECU per year. There is a strong interest from industry for the fuel cell technology and one may say that there is well integrated approach for the development of fuel cells in which utilities, manufacturers and the government (MITI and NEDO) participate.

During the eighties fuel cell R&D was mainly aimed at PAFC. In 1983 a US 4.5 MW prototype PAFC plant manufactured by IFC was installed at the electric utility TEPCO near Tokyo. Until around 1991 most of the public funding was allocated for PAFC development; in particular for the development of two 1 MW PAFC prototype plants constructed by Japanese companies, with in each plant 4 PAFC stacks of 250 kW. In total eight 250 kW stacks have been developed by 4 companies as a part of the MITI policy to stimulate competition. The size of 1 MW and the stacks of 250 kW allowed a flexible approach with the possibility to scale up to larger sizes of > 5 MW or to concentrate on smaller PAFC of around 200-400 kW. After completion and testing of the two 1 MW plants it was realized that the cost of solving the problems of reliability with a required lifetime of 40.000 hours, would be prohibitive. It was therefore decided to concentrate on smaller 200-400 kW PAFC. Of the four participating companies the two best: Fuji Electric and Mitsubishi Electric were selected for the further development of 200-400 kW PAFC. At present PAFC in Japan are expected to be commercial in 3 to 5 years and public funding is now mainly limited to demonstration projects. Six MECU per year is spent to subsidize 30% of the capital and installation cost of PAFC demonstration plants. This allows the construction of 15 PAFC plants per year. By far the major part of the cost of PAFC development in Japan is presently born by industry and utilities. As for large PAFC plants, a 11 MW has been recently constructed for the utility TEPCO in Japan by the US company IFC and the Japanese company Toshiba.

Since 1991 the emphasis of funding has changed from PAFC to MCFC. Also here the strategy of MITI was to stimulate competition. Four companies were asked to develop 10 kW MCFC stacks. The most promising concepts developed by Hitachi and IHI were selected for scaling up to 100 kW, which have been recently realized. The next stage of development is the construction of a 1 MW ER-MCFC which is expected to be ready in 1997. In parallel IR-MCFC is being developed by Mitsubishi Electric, first in collaboration with the US company ERC but during the last years more independently; a 30 kW IR-MCFC has been constructed and a lifetime of 10.000 hours has been obtained until now, with lifetime tests being continued.

As for SOFC public funding has been limited. Utilities acquired 3 and 25 kW SOFC units from the US company Westinghouse the get experience with this fuel cell technology. Recently around 8 companies started, with own funds, the development of SOFC prototypes of typically 1 kW.

Finally limited activities are going on in the field of SPFC.

US

Fuel cell research has been going on for many years and presently public funding amounts to around 60 MECU per year; industry is spending a similar amount. Main US funding organizations are the Department of Energy (DOE), the Gas Research Institute (GRI) and the Electric Power Research Institute (EPRI)

Since many years IFC is developing PAFC systems. A pilot PAFC production line has been set up and around fifty 200 kW plants have been sold; the cost of 3000 to 4000 ECU per kW is still too high for PAFC to be commercially attractive. In 1987 IFC together with utilities such as EPRI developed a plan to develop and commercialize twenty 11MW PAFC plants; only one plant was realized in collaboration with the Japanese company Toshiba. This 11 MW plant is presently operational near Tokyo.

Three companies are involved in the development of MCFC: IFC, IGT and ERC. IGT is presently developing a 250 kW ER-MCFC and ERC aims at the development of a 2 MW MCFC plant in 1995. Funding for the 2 MW MCFC plant has been brought together by a consortium of 18 utilities thus sharing the risk of introducing this new technology. The US- DOE will allocate 26 MECU for MCFC in 1994 as a part of a five year programme for MCFC development which amounts to 130 MECU.

Westinghouse is world leader in the development of SOFC. 25 kW prototype plants have been constructed and tested in the US and Japan. The development of 100 kW plants is presently under way. Last year a 5 year programme for the further development of four 100 kW and one 1 MW SOFC plants was approved with a budget of 120 MECU; the US DOE contributes 60 MECU

Recently interest for fuel cells in transport applications strongly increased. At present 15 MECU per year is spent on the development of PAFC and SPFC driven vehicles ; this includes the development of a fuel cell driven passenger car by General Motors and a PAFC driven bus. A "National Program Plan Fuel Cells in Transportation" is presently being discussed and may lead to strongly increased funding. SPFC is here an important candidate but also PAFC, DMFC and SOFC are being considered; the last fuel cell type in particular for heavy duty transportation.

APPRAISAL OF THE FUEL CELL TECHNOLOGY

General appraisal

Fuel cell research in the world has now been going on for at least thirty years. Although much money has been spent on R,D&D, fuel cells have not yet found even a small market. PAFC are said to be commercial within 3 to 5 years but this may well last longer. There may even be a danger that interest for this environmentally friendly technology will vanish, when fuel cells will not be commercialized in the next ten years for at least some applications. It is therefore important to try to identify possible causes for this slow development and to define a R,D&D strategy which can speed up fuel cell commercialization.

In this context it is interesting to look at the development of another energy conversion technology, which was successfully commercialized: the gas turbine.

Gas turbines were developed in the fourties for military planes where cost did not play a role. In the fifties gas turbines found first commercial applications in civil aviation, where the short lifetime was not a problem and where an overhaul occurred every 200-300 hours. In the sixties gas turbines started to find applications in peak load electricity generation on a large scale. This application fitted the state of the art of gas turbines at that time; they had a short lifetime and a low efficiency, but the cost per kW was low in particular for large installations due to a strong economy scale. Presently gas turbines are suitable for base load electricity production. They have long lifetimes, require an overhaul only every 40.000 hours and have high efficiencies.

The introduction of gas turbines was successful mainly due to the fact that commercial applications were identified in an early stage of their development. An additional advantage was the fact that these applications in the beginning of gas turbine development, did not require long lifetimes. The main advantages of gas turbines were: high power with a simple system with few components, low cost due to a strong economy of scale, high power density and fast delivery and installation.

The development of fuel cells (mainly PAFC, MCFC and SOFC) went very differently. During the last thirty years no commercial applications were identified. Possible causes for the slow progress may be the following:

Fuel cell development in the past was aimed too much at imitating existing large scale electricity generation systems which have a reliable operation for 50 to 100.000 hours. The high cost of fuel cells and the idea that fuel cell plants should in the long term replace large centralized power plants with very long lifetimes, led to the generally accepted view that fuel cells should, in the long term, be large (of the order of hundreds of MW) and have a reliable operation of at least 40.000 hours.

In a strategy which aims at the replacement of conventional electricity production systems by fuel cells , the high efficiency for electricity production of fuel cells was seen as an major asset. R&D was therefore aimed at options which lead to a high efficiency for electricity production; a choice was made for:

- High temperature fuel cells such as MCFC and SOFC stacks which have a high efficiency but which cost 2 to 3 times more than low temperature SPFC and AFC;
- Integrated systems of fuel cell stacks, reformers and other components which are optimized for a high overall efficiency but which are complicated and expensive;

This drive for high efficiency led to expensive systems which require long lifetimes, of the order of 40.000, to obtain acceptable payback times.

Fuel cell plants developed until now are generally integrated systems which contain components with an economy of scale (the reformer and purification equipment) and components which are modular (the stack). The drawback is that small integrated systems are expensive because they contain components with an economy of scale which have a high cost per kW when they are small; large integrated systems are expensive because only a part of the system has an economy of scale.

In a drive to achieve large fuel cell plants as quickly as possible both in the past and present, fuel cell systems have been and are scaled up to MW size too fast. This was demonstrated by two 1 MW PAFC plants in Japan. After completion it was realized that the cost of solving the problems of reliability with a required lifetime of 40.000 hours for MW size plants, would be too high. The next step was therefore not the scaling up to 10 or 20 MW as was generally expected; instead further development was concentrated on smaller 200-400 kW PAFC. The construction of a single MW size plant can not possibly guarantee reliable operation for 40.000 hours, which is requested by the client. Demonstration of reliable operation for such fuel cell power plants would require a large number of MW size plants and is prohibitively expensive.

As compared with gas turbine development where applications with increasing lifetime requirements were successively identified, the fuel cell approach aimed directly at 40.000 hours, this is really the hard way to bring about a break through for a new technology.

Appraisal and problem areas of high temperature fuel cells.

High temperature fuel cell systems such as PAFC, MCFC and SOFC are envisaged for electricity production and cogeneration in buildings and industry. Due to their high cost, lifetimes have to be long (40.000 hours) to get reasonable payback times; lifetime tests are therefore time consuming and costly.

PAFC are presently being development by Japanese and US companies. This fuel cell type is expected to be commercial in three to five years. A reliable operation for 40.000 hours can not yet be guaranteed and extensive tests are presently going on in Japan and the US to improve reliability. The cost of PAFC systems is presently too high; mass production at the scale of 50-100 MW per year, through massive use of PAFC in industries, could bring the cost of PAFC systems down to acceptable levels of around 2000 ECU/kW. This cost reduction path requires no R&D activities nor technological demonstration activities since the PAFC technology is "off-the-shelf". Industrial strategy encouraging industries to massively use PAFC through financial support is beyond the scope of this R,D&D Strategy document.

MCFC are being developed in Europe and European industry is strongly involved. MCFC operates at 650°C and is expected to achieve efficiencies of 60 to 65% in the long term. This type of fuel cell is likely to be expensive due high temperature production techniques and operation, the very corrosive carbonate electrolyte, the low current density of 0.15 A/cm^2, the need to transfer CO_2 from the cathode to the anode, the low tolerance for sulfur (« 1 ppm) and, in case of ER-MCFC, the need for reformers or coal gasifiers. High temperature production techniques for the ceramic and metallic MCFC components are expensive; still much R,D&D is needed to reduce the cost. The present operating temperature of 650°C of MCFC leads to a high cost for the stack and auxiliary parts such as heat exchangers for the preheating of air and fuel gas. The very corrosive carbonate electrolyte is an important cause of the high cost and of the slow progress in MCFC research; it is also an important barrier for a rapid commercialization. Major problems are: nickel dissolution at the cathode and deposition in the electrolyte causing short circuits (in particular with pressurized operation), corrosion of the bipolar plate and electrolyte management. The low current density of 0.15 A/cm^2 also leads to high stack cost per kW. Materials research is needed to find ways to increase the current density considerably and to solve the problems of corrosion. In addition the following points, are important for MCFC:

- Systems should be kept simple and in particular MCFC prototypes and demonstration projects should be designed for operation at one bar; the problem of nickel dissolution is then hardly relevant and a compressor is not needed.
- MCFC R,D&D should be focussed on simple modular concepts without an external reformer (IR-MCFC) or on MCFC with a modular reformer which can be easily be mass produced (IIR-MCFC).

SOFC consist of ceramic components, operate at 1000°C and are expected to have efficiencies of 60-65% in the long term. The SOFC have a number of advantages as compared with MCFC. For SOFC corrosion is, contrary to the MCFC, not a serious problem; already 15 years ago SOFC cells obtained life times of 50.000 hours at BBC in Germany. Another advantage as compared with MCFC, is the fact that the SOFC, with its solid electrolyte does not have problems with electrolyte management. Further on the current density of SOFC, which already now is 2 to 4 times higher than for MCFC, still has much potential for further improvement; this is an important route for cost reduction of SOFC. Finally the problems connected with internal reforming of methane in SOFC may be more easy to solve than for MCFC.

Both in Europe and Japan many organizations presently develop SOFC prototypes of the order of 1 kW. The US company Westinghouse is most advanced with its tubular SOFC concept of which 25 kW prototypes are presently operational. The efficiencies obtained with these units however were below 40% even when pure hydrogen was used as a fuel. It is generally agreed that the tubular SOFC concept of Westinghouse is not likely to be cost effective due to the batch type production methods and the 4 hour long heating up and cooling down period required for each coating operation. The vast majority of SOFC projects focusses on flat plate or other SOFC concepts which are expected to have a higher probability to achieve cost effectiveness.

Even with these concepts SOFC is likely to be expensive due to high temperature production techniques and operation. High temperature production techniques for the ceramic SOFC components are expensive and still require much R,D&D to reduce the cost. The present operating temperature of 1000°C for SOFC leads to a high cost for the auxiliary parts such as heat exchangers, piping etc. At this temperature heat exchangers for preheating air and natural gas will have to be of a ceramic material, this will lead to a prohibitive high cost. Even operation at 900°C, which would allow metallic heat exchangers, would still lead to a heat exchanger cost of 1000 to 1500 ECU/kW. Lower operating temperatures of 800 to 850°C for SOFC are therefore an important objective. Such a lower operating temperature would also be advantageous for the process of internal reforming which requires around 750°C and which goes too fast at 1000°C. A disadvantage is that current densities at 800°C will be lower than at 1000°C, but preliminary experiments have shown that 0.3 A/cm^2 may be possible; this is still considerably higher than for MCFC. A serious drawback of SOFC is the brittleness of the ceramic components. This is a major barrier for scaling up to MW size SOFC power plants. For PAFC and MCFC the standard cell size lie around 0.5 to 1 m^2, whereas the typical cell size of a SOFC cell does not exceed 0.1 to 0.2 m^2. Although the higher current density of SOFC may compensate for the smaller cell size, it is crucial, in particular in view of scaling up and of cost reduction, to find ways to increase the cell surface of SOFC; the multicell array developed by Siemens is here a very promising concept. SOFC concepts should be developed which are simple and modular; IR-SOFC is an important option.

Appraisal and problem areas for low temperature fuel cells.

The two best known low temperature fuel cells are AFC and SPFC; the DMFC, with a polymer membrane, which is presently being developed, is a special type of SPFC.

AFC operate at around 80°C and use a liquid alkaline electrolyte; the efficiency with hydrogen is 50 to 60%. The cost of the stacks is expected to be considerably lower than for MCFC and SOFC due to high current densities and low temperature operation. They have been used extensively in space craft but are of limited interest for terrestrial applications with natural gas or methanol. With these fuels a reformer is needed which causes problems due to the fact that CO and CO_2 in the reformer gases (and CO_2 in air) impair the operation of the alkaline fuel cell. This would require purification equipment both at the air and fuel side of the fuel cell leading to a higher cost. AFC is therefore limited to use of pure hydrogen. CO_2 in air would then still be a complication which would make systems of 20-200 kW unattractive. Another drawback is the fact that at room temperature only a small part of the rated power is available. Cheap mass production may be possible with matrix electrolytes.

SPFC operate at 80°C, have presently efficiencies of 40% with natural gas and deliver heat of a temperature somewhat lower than 80°C. Although the performance of this fuel cell type is not very spectacular and considerably lower than MCFC or SOFC, it does have, like other fuel cell types, very low pollutant emission levels. The major advantage of SPFC is its potential for achieving a very low cost in particular for the stack; a cost of 200 ECU/kW is expected in the long term. Factors which contribute to such a low cost are: the high current density of 1 to 2 A/cm^2; the low temperature of operation which allows very cheap heat exchangers for the preheating of air and fuel; cheap mass manufacturing methods (eg. membrane electrode assemblies). Due to this low cost SPFC may be the only fuel cell type which is economically feasible for road traction. Other applications may be found in cogeneration for buildings where waste heat of 80°C can be used. An important advantage of the low cost is that also applications with a short lifetime between 3000 and 10.000 hours may have acceptable payback times. This could lead to SPFC achieving commercial applications in a relatively short time due to shorter and less costly lifetime tests.
Improvement of the efficiency and lifetime can then lead to other commercial applications
at a later date.

With the present state of the art the performance and lifetime of SPFC is sufficient for applications such as transportation and domestic cogeneration and there are no major technical problems for utilization of SPFC. The major barrier for implementation of SPFC is the high cost of SPFC stacks. **R&D should therefore be focussed on the development of cheap manufacturing methods for SPFC; with the aim to produce SPFC stacks with a cost of 200 ECU/kW.**

In parallel to these main lines of research a number of longer term issues should be addressed:

Basic R&D to improve the SPFC such as reduction of the Pt catalyst load, reduction of the sensitivity for CO, development of cost effective SPFC which do not require pressurized operation, development of SPFC which operate at 130°C, etc.

One of the longer term options is the DMFC which oxidizes methanol directly and does not require a reformer. This concept is basically a stack which uses methanol. DMFC stacks can, like SPFC stacks, be cheaply mass produced. The use of methanol assures simple fuel storage, distribution, etc. and avoids the complications of hydrogen. This very interesting DMFC concept should be further developed, in particular in view of the promising results which have been recently obtained.

Another option for SPFC is the use of natural gas or methanol; here reformers are needed; this will lead to integrated more complicated systems. Although this type of system is not given a high priority; it is important to keep this option open.

ELEMENTS OF A FUTURE EUROPEAN FUEL CELL STRATEGY.

In a reorientation of fuel cell development which aims at a rapid progress and commercialization, cost reduction, simplification and reliability should be the major objectives in the next ten years.

Cost reduction should be a major objective

In view of the possibilities for a rapid progress and cost reduction, R,D&D on SPFC development should be strongly emphasized; the aim for the next ten years is to produce SPFC with a cost of 200 ECU/kW

Since several years R,D&D is carried out on a new fuel cell type: the SPFC. Due to its high power density, low temperature of operation, and short cold start up time this fuel cell type is suitable for applications such as road transportation. Other applications may be identified such as domestic cogeneration, back up systems etc.

SPFC have a strong potential for cost reduction and in the long term the stack cost may be as low as 200 ECU/KW; SPFC stacks are expected to be 2 to 3 times cheaper than high temperature fuel cell stacks (MCFC and SOFC); this due to the fact that:

- The current density of SPFC is 4 to 8 times higher;
- Membrane electrode assemblies offer possibilities for cheap manufacturing; MCFC and SOFC use expensive, high temperature, ceramic production techniques;
- Recycling of CO_2 like in MCFC is not needed;
- Low temperature operation of SPFC is very advantageous as it does not require expensive, corrosion resistant materials. Preheating of air and fuel at 80°C in SPFC can be realized with cheap plastic heat exchangers. This contrary to preheating of air and fuel in MCFC and SOFC which requires 8 and 13 times more heat to be exchanged; preheating heat exchangers in MCFC and SOFC are therefore expensive (for SOFC at 900°C: 1500 ECU/ kWel)

SPFC stacks have lower efficiencies than MCFC and SOFC but their low cost is a major asset. Due to this low cost SPFC may become economically feasible for applications which require short lifetimes of 3000 to 10.000 hours such as transportation. Such short lifetimes could speed up the progress of fuel cell R,D&D considerably. A development similar to that of gas turbines might be possible where progress in development may lead to reliable operation during longer lifetimes, to higher efficiencies and to new commercial applications. The low pollutant emission is one of the major assets of fuel cells and here SPFC perform as well as high temperature fuel cells. SPFC may have a major impact on pollutant abatement in:

- Road traction where the efficiency of 40-50% for SPFC is much better than the efficiency of petrol engines which is around 15-20%;
- Commercial and domestic cogeneration where 80°C heat can be used for heating of buildings leading to a high overall efficiency.

To profit most from the low cost of stacks, hydrogen should be preferably used as a fuel. For natural gas or methanol fueled SPFC, which are most promising in a size of 20 to 200 kW, the advantage of very low cost stacks, is off set by the high cost of reformers which are very expensive for this size. For the use of natural gas in SPFC the concept of a fuel cell network is proposed which will be described below. This concept consists of a central fuel processor (reformer and purification) producing pure hydrogen which will be fed in a network of pipelines to fuel cell stacks near users. The stack duty is optimized for production of heat and electricity. The hydrogen from the fuel processor can also be used for fuel cell driven buses in public transport.

It is the aim to come to a to first commercialization of SPFC for cogeneration applications in buildings in 5 to 7 years and for transportation at a later stage.

Continuation of R,D&D on high temperature fuel cells

R,D&D on high temperature fuel cells for industrial cogeneration and large scale electricity production should be continued. Although SPFC stacks are expected to be considerably cheaper than MCFC and SOFC stacks, they have the disadvantage that their operating temperature is low and that the waste heat of around 80°C can only be used for cogeneration applications in buildings and not for industrial cogeneration which requires heat in the range of 100 to 1500°C. It is therefore proposed to continue R&D on SOFC and MCFC, which can deliver high temperature waste heat in a range of 100 to 900°C and are suitable for industrial cogeneration. MCFC and SOFC may also be more suitable for large scale (MW size) electricity production, due to the fact that their efficiency for electricity production is higher than for SPFC. Commercialization of MCFC and SOFC may be expected in 10 to 15 years. The first market opportunities are simple fuel cells for use with pure hydrogen or syn gas from coal or biomass gasifiers to be used in the networks described below. Internal reforming SOFC and MCFC still require much R,D&D to solve a number of technical problems; they are a longer term option.

Simplification of systems: fuel cell networks and modular systems

The measure of complexity of systems is an important factor which strongly influences reliability and cost. The optimization of the efficiency of electricity production is pursued by the integration of the stack, reformer purification equipment and other components. This leads to complicated and expensive systems with many components;in particular for fuel cell systems with external reformers such as PAFC and ER-MCFC. This complexity and the requirement of reliable operation for 40.000 hours is an important cause of the slow progress of fuel cell R,D&D in particular for high temperature fuel cells.

One way to speed up R,D&D is to focus on development of concepts which require a minimum of auxiliary equipment, which can lead to a simplification and cost reduction of systems. Presently in integrated fuel cell systems a part of the system (reformer and purification equipment) has a economy of scale and another part (fuel cell stack) is modular. The drawback is that small integrated systems are expensive because they contain components with an economy of scale of which the cost per kW is high when they are small; large integrated systems are expensive because only a part of the system has an economy of scale. Two lines of development are proposed to cope with this problem:

- Development of fuel cell networks where components with an economy of scale and modular components are not integrated but optimized separately. Such fuel cell networks consist of a central MW size reformer and purification equipment (optimized for economy of scale) producing pure hydrogen which is fed in a pipeline network to a number of fuel cells near the user; these stacks are optimized for production of electricity and heat. Such networks with SPFC could be constructed in 3-5 years.
- Another major option is the development of systems which do not require an external reformer. This results in simple and cheap systems which have a more modular character, and are more suitable for cheap mass production. R,D&D should therefore be focussed on development of internal reforming MCFC and SOFC and direct methanol fuel cells (DMFC). This option will still require much research and may be commercialized in 10-15 years.

Fuel cell networks

Fuel cell networks can lead to simplification by separate optimization of the reformer and stacks. This could solve the problem that a mixture of modular components and components with an economy of scale, leads to a high cost for both small and large systems. Such a separate optimization of the fuel processor (reformer or a gasifier for the coal or biomass) and the stack is also likely to lead to improved reliability. In such a concept the fuel processor (reformer or gasifier) could be large which leads to a low cost per kW due to the economy of scale. The fuel (hydrogen, coalgas or biogas) could be transported, via a local pipeline network, to a number of dispersed fuel cell stacks, near the user, which produce heat and electricity tailored to his needs; in case reformers are used, the produced hydrogen can also be used in fuel cell driven vehicles such as buses for public transportation. The modular character of the stacks would allow cheap mass manufacturing and a low cost. The option with a coal or biomass gasifier is important as it allows the use of fuel cells in combination with coal and renewable energy. By separating the fuel processor (with an economy of scale) and the modular stacks in the way described above, the speed of progress will be considerably increased as reformers and gasifiers (for coal and biomass) optimized for fuel production are already commercially available. A drawback of this concept is the fact that the overall energy efficiency is likely to be somewhat lower as compared to the integrated concept. In particular for low temperature fuel cells such as SPFC, integration of reformer and stack will not bring much improvement in the overall efficiency due to the fact that the waste heat of this fuel cell is only 80°C; the separate optimization of reformer and SPFC stacks may well be more advantageous. Computer simulation studies should be carried out to explore these options.

This concept could lead to a rapid commercialization because:

- The reformer and purification equipment are commercially available and have a low cost per kW at a size of typically 2-5 MW due to their economy of scale;
- The cost of the hydrogen pipeline network is expected to be of the same order as a pipeline network for natural gas.
- The fuel cell stacks (for cogeneration and transportation) are modular and can be cheaply mass produced. The availability of pure hydrogen will remove the technological issue of CO poisoning in SPFC and will double the current density leading to considerable cost reductions for the stack;
- The use of fuel cells for cogeneration will lead to a high overall efficiency (the sum of electricity and heat production). The efficiency of 40-50% of fuel cell driven buses is 2 times higher than in conventional transportation. Pollution levels will be 10 to 1000 times lower than in conventional systems.

Such a concept also offers the possibility for collaboration as stacks from different companies and even of different fuel cell types, such as PAFC MCFC and SOFC, could be tested in one demonstration project with the same reformer or coal gasifier. The fuel cell network could be realized in 3-5 years

Simple modular fuel cell systems without external reformers

In a strategy aiming at cost reduction of products two options exist:

- The cost of a system with an economy of scale can be reduced by making it large;
- The cost of a modular system can be reduced by cheap mass production.

In fuel cell networks cost reduction can be achieved by the separate optimization of components with an economy of scale and of modular components. Another option is the development of fuel cell systems which have mainly a modular character and which have few components with an economy of scale. Three options are possible:

- Simple stacks which use hydrogen or coalgas as a fuel. They can be expected to be available in the short and medium term and can be used in fuel cell networks;
- Development of systems which do not require an external reformer such as internal reforming MCFC and SOFC and DMFC. These systems still require much research and may be commercial in 10-15 years;
- Development of reformers which are modular and can be easily mass produced such as indirect internal reforming IIR-MCFC with modular reformers in the stack; one reformer for every 5 cells.

Balance of plant (BOP)

In order to speed up SOFC and MCFC development, balance of plant (BOP) lifetime tests should be carried out with systems which include all auxiliary components and a simulated fuel cell stack. These tests should be combined with the development of good system simulation models.

Even simple systems consist of many components and the failure of one component could be sufficient to impair the operation of the system. Apart from the stack most components are commercially available and could be tested immediately. It is therefore proposed to start balance of plant (BOP) life time tests for high temperature fuel cell systems with all required auxiliary equipment and a simulated fuel cell stack. By doing these tests in parallel to MCFC and SOFC stack development, R,D&D could be accelerated considerably. The aim is to identify possible problem areas for reliable operation caused by non-stack components. The importance of such tests is highlighted by past experience with PAFC which showed that reliability problems are mainly caused by non-stack components; stack operation was generally reliable.

Reliability, plant size and demonstration

Reliability and maintenance are important issues for a breakthrough of fuel cells. Before a new technology can be commercialized it is crucial that reliable operation for the required lifetime of a particular application can be guaranteed. The required lifetime depends on the type of application and can range from 40.000 hours for stationary electricity generation to 3000 hours in passenger cars. Factors which influence reliability are corrosion, complexity of systems and the reliability of single components.

Many systems have to be tested before a guarantee for reliable operation can be given. Demonstration projects play here a very important role. They should give information on the lifetime of different components and identify those components which are critical for the lifetime of the system.

Demonstration projects should also give information on the total capital and operational costs including maintenance, service and replacement of parts, during the entire lifetime of the system. In particular information on maintenance costs for different fuel cell types is very scarce. Demonstration projects should provide that type of information. In particular it is crucial for the market chances of fuel cells to establish whether unmanned, automatic operation with low maintenance costs is possible. Another aspect which may be explored in the proposed fuel cell networks is the possibility to adapt the electricity supply of a number of dispersed small fuel cell power plants to the demand, by remote control (similar to demand side management). This applies both to high temperature and low temperature fuel cell networks.

Finally in a reorientation of fuel cell development it is important to abandon the idea of 100 MW fuel cell power plants. **In the next 10 years even the cost of demonstrating reliable operation for 40.000 hours of 1 to 10 MW is prohibitive and R,D&D should be focussed on reliability tests for systems which are not larger than 300 kW.**

PROPOSED EUROPEAN FUEL CELL R,D&D FOR THE NEXT TEN YEARS

Fuel cell research in the world has now been going on for at least thirty years. Although much money has been spent on R,D&D, fuel cells have not yet found even a small market. During these thirty years research was characterized by a strong emphasis on obtaining high efficiencies for electricity production and on development of high temperature fuel cells such as PAFC, MCFC and SOFC for electricity production and cogeneration. They have the disadvantage of a high cost, which results in long required lifetimes of around 40.000 hours. This led to time consuming reliability tests and the slow progress of fuel cell R,D&D. Below a number R,D&D actions are proposed which could lead to an acceleration of fuel cell R,D&D, cost reduction and commercialization for some applications in the next ten years:

R&D on low temperature fuel cells

In view of the possibilities for rapid progress and cost reduction the development of cheap SPFC and possibly AFC stacks should be strongly emphasized; in particular to be included in low temperature fuel cell networks and electric vehicles discussed below. Topics proposed are:

- R&D on the development of cheap manufacturing methods for SPFC should have a high priority; in particular the use of membrane electrode assemblies (MEA) which have the potential of producing a fuel cell laminate in a continuous and cheap way. The bipolar plate is here the bottleneck for cheap mass manufacturing and R&D should be focussed on the development of bipolar plates which are suitable for cheap mass production. This R&D should result in prototype pilot production plants which produce SPFC stacks at a cost of 200 ECU/kW;
- Carry out a feasibility study to identify the best structure, application and location for a 2-5 MW urban fuel cell network with a reformer and low temperature fuel cells;
- Development of SPFC driven vehicles; in particular buses for public urban transportation;

In parallel R&D will be carried out on more advanced low temperature fuel cells:

- Basic R&D to improve the SPFC such as reduction of the Pt load, reduce the sensitivity for CO, develop cost effective SPFC which do not require pressurized operation. An important topic for basic research is the development of a SPFC which operates at 130°C. An increase from the present operating temperature of 80°C to 130°C would widen the field of applications and is requested by potential users of SPFC. The key issue is here the development of solid electrolytes which are chemically and physically stable at 130°C;
- DMFC operating at 130°C should be developed. The key issue is the development of a suitable solid organic electrolyte which allows a high current density, has a low methanol diffusion and is physically and chemically stable at 130°; other topics are the development of suitable catalysts and reduction of the Pt load. Even although the requirements for SPFC and DMFC membranes are different, R,D&D on membranes for SPFC and DMFC is closely linked with many synergies.In parallel to membrane development DMFC should be scaled up with existing membranes to modules of 10 kW; the envisaged current density is 0.5A/cm^2 at 0.6 V and the Pt load should be smaller than 1 mgr per cm^2;
- Another option for SPFC is the use of natural gas or methanol; here reformers are needed; this will lead to integrated more complicated systems. Although this type of system is not given a high priority it is important to keep this option open. A key issue is here the development of cheap manufacturing methods for reformers.If reformers could be cheaply manufactured, like car engines, small integrated systems fueled with natural gas or methanol may have a chance in particular for stationary applications such as cogeneration in buildings;

Demonstration of an urban fuel cell network for clean cogeneration and transport

From what has been said before the most promising option in terms of cost-effectiveness is a fuel cell network as described before with the cheapest fuel cell type: the SPFC. It is therefore proposed to demonstrate the feasibility of the fuel cell technology with an **Urban fuel cell network using SPFC for clean cogeneration in domestic and commercial applications and transportation.** Although such a network still has to be defined it will have a number of the following characteristics:

- A large 2-5 MW reformer, producing pure hydrogen, is connected, via a local network of pipelines, with a number of fuel cell stacks for domestic and commercial cogeneration near the user; this would also allow a collaboration between different SPFC and AFC manufacturers as different stacks can be tested with the same fuel processor.
- The reformers are commercially available;
- As described before parallel R&D will aim at the development of cheap manufacturing methods for SPFC stacks and at the construction of a pilot production line;
- Hydrogen produced by the reformer can also be used as fuel for fuel cell driven cars and buses;
- Low cost MCFC and SOFC stacks for industrial cogeneration and developed within the next 3-4 years can also be included in such a network;
- Hydrogen from renewable sources could be used;
- Remote control could be used to adapt electricity production of the stacks to the overall demand (similar to demand side management);
- The project should start with a feasibility study to identify the best structure, field of application and location.

Demonstration of fuel cell driven electric vehicles

In case fuel cell driven vehicles have achieved technical feasibility, the economic feasibility of the vehicles will be demonstrated in FC EV fleets. In particular buses for public transport where the allowable cost is expected to be higher than for passenger cars.

R&D on high temperature fuel cells

For high temperature fuel cell systems, R,D&D should be focussed on actions which can lead to simple, modular and low cost systems:

- Development of cheap mass production methods for simple MCFC and SOFC stacks for hydrogen or coal gas which can be included in the fuel cell networks; the bipolar plate is here an important bottleneck. MCFC should operate at one bar, where the problem of nickel dissolution is not relevant and a compressor is not needed; this action should lead to the construction of pilot production lines;

- Feasibility study to identify the best structure, field of application and location for an 5-10 MW industrial fuel cell network with a coal or biomass gasifier and MCFC and SOFC stacks;
- In order to come to low cost high temperature fuel cells R,D&D should be focussed on simple , modular and low cost fuel cell systems which do not require an external reformer such as:
    - IR-MCFC and IR-SOFC which use natural gas;
    - Development of reformers which are modular and can be easily mass produced (eg. IIR-MCFC)
- In the coming 10 years R,D&D should be focussed on demonstrating the reliability of MCFC plants up to 300 kW for 40.000 hours operation; the cost of demonstrating the reliability of MW systems is expected to be prohibitively expensive. Even tests with 300 kW will be so expensive and time consuming that pooling of MCFC funds and know how would be highly desirable. The proposed high temperature fuel cell network may be a possibility for collaboration;
- SOFC should be scaled up to 100-200 kW, initially still operating at 1000°C and at 800°C at a later stage. In the next ten years extensive life time tests of 100 to 200 kW SOFC should be carried out to demonstrate the reliable operation for 40.000 hours.
- In order to speed up SOFC and MCFC development, balance of plant (BOP) lifetime tests should be carried out with systems which include all auxiliary components and a simulated fuel cell stack. The aim is to identify possible problem areas for reliable operation caused by non-stack components. The importance of such tests is highlighted by past experience with PAFC which showed that reliability problems are mainly caused by non-stack components. Identification of such problems with non- stack components, even when the stack is not yet fully developed could speed up R,D&D considerably.
- System optimization even for simple systems is very important for cost reduction and improved reliability. Development of system simulation models for MCFC and SOFC systems are crucial for system optimization.

In parallel more basic material and systems research should be aimed at longer term SOFC and MCFC options:

- For pressurized MCFC, which have higher efficiencies, the problem of nickel dissolution should be addressed. An important longer term R&D topic is the increase of the current density for MCFC; this should lead to a lower cost for MCFC stacks;
- For reasons given above a major R&D effort should be focussed on the development of cost effective SOFC operating at 800 to 900°C. First experiments have demonstrated that current densities of 0.3 A/cm^2 are possible at these lower temperatures. Also the problem of the small cell size due to the brittleness of the ceramic components should be addressed;
- Development of low temperature SOFC operating at 500°C for internal reforming of methanol.

Demonstration of a industrial high temperature fuel cell network

Demonstration of a 5-10 MW high temperature fuel cell network with a coal or biomass gasifier and high temperature fuel cells for industrial cogeneration is foreseen in 5 to 7 years when MCFC and SOFC can be expected to be more advanced. Such a concept offers the possibility for collaboration as stacks from different companies and even of different fuel cell types, such as MCFC and SOFC, could be tested in one demonstration project with the same gasifier. This project would include the following actions:

- Development and demonstration of fuel cell networks for industrial cogeneration with a coal or biomass gasifier and MCFC and/or SOFC stacks;
- As described before parallel R&D will aim at the development of cheap production methods for MCFC and SOFC stacks; starting with the most simple stacks.
- Remote control of the electricity production of single stacks to adapt the supply to the overall demand;
- The project should start with a feasibility study to identify the best structure, field of application and location.

Demonstration of stand alone fuel cell systems

In case fuel cell networks will turn out not to be feasible, stand alone low and high temperature fuel cell systems will be supported if they come closer to the market and have a promise of cost effectiveness.

Demonstration of PAFC

Some funding should be made available for the development and demonstration of PAFC. However as European companies are not involved in PAFC development, funding for PAFC should not have a high priority. Some funding could be made available for PAFC demonstration plants to get utilities and other organizations acquainted with the fuel cell technology. Priority should be given to innovative applications such as PAFC with absorption heatpumps; PAFC as a charging station for EV etc. A close collaboration should be brought about between organizations which carry out such demonstration projects in order to exchange experience.

IMPLEMENTATION

The above proposed fuel cell programme for ten years should be carried out in close collaboration with different services in the Commission and with national and industrial programmes.

The services in the Commission concerned are JOULE, BRITE and THERMIE; they are presently all involved in fuel cell R,D&D. Development of cheap manufacturing methods for different types of materials, fuel cell stacks and other components would best fit in the BRITE programme. The demonstration and reliability tests of fuel cell systems, fuel cell driven vehicles and the proposed low and high temperature fuel cell networks would be suitable for THERMIE. All other topics such as basic materials R&D, cell, stack and system design and development, system modeling could be carried out in the JOULE programme. A close collaboration is envisaged between the three EC programmes.

As for collaboration between national, industrial and EC programmes. The EC can play an important role in bringing about a collaboration and information exchange between most of the fuel cell programmes in Europe. This is brought about by EC projects which have the condition that several partners from different EU member states should participate; most of these organizations are also involved in national and industrial fuel cell activities. In addition regular EC fuel cell contractor meetings can assure a continuous contact and information exchange between major fuel cell groups in Europe.

An interesting possibility for collaboration between potential users and manufacturers is the funding of a 2 MW MCFC plant by 18 utilities in the US. A close collaboration between fuel cell users and manufacturers is very important for the commercialization of fuel cells. The above example has the advantage that users are involved in the design of fuel cell systems and that the financial risk is limited. Such structures could be of interest for fuel cell development in Europe.

Collaboration between Europe and the US and Japan takes mainly place on an industrial level: DB (D) and VSEL (UK) collaborate with Ballard (Canada) in the development of SPFC; in the field of MCFC MTU (D) collaborates with ERC (US) and BCN (NL) with IGT (US). For PAFC, which are only produced by Japanese and US companies, collaboration with Japan and the US is a prerequisite for having PAFC prototypes in Europe. Other fields of collaboration can be envisaged where activities of European companies and US or Japanese companies are complementary (eg a US company for membrane development and a European company for SPFC development). The collaboration with the US and Japan on government level is limited to information exchange. In the past a number of common fuel cell conferences have been organized.

FUNDING

Below some rough estimates are made for funding requirement for the different fuel cell technologies; taking into account the possibilities for funding within the EC. Required EC funding for the development of SPFC, MCFC and SOFC amounts to around 30-40

MECU for each of these technologies. The funding for SPFC should be mainly spent in the next 5 years. The proposed funding for MCFC and SOFC would be more evenly spread over the coming 10 years. Both the low temperature urban fuel cell network network and the high temperature industrial cogeneration network will require EC funding of around 15 and 30 MECU respectively. The urban fuel cell network could start in 2 years and the high temperature network in 5 to 7 years. For the development and demonstration of fuel cell driven electric vehicles 30 MECU should be envisaged. This amounts to a total EU funding of around 160 MECU for a ten year period.