ENVIRONMENTAL POLICY RESEARCH CENTRE
Freie Universität Berlin
Department of Political and Social Sciences
Otto Suhr Institut for Political Sciences

FFU-report 10-2003

Environmental Policy
Research Centre

ffu

Lead markets for fuel cells in stationary applications

Klaus Jacob

Klaus Jacob
Environmental Policy Research Centre
Freie Universität Berlin
Ihnestrasse 22
14195 Berlin
Phone: ++49 (0)30 83854492
Fax: ++49 (0)30 83856685
E-Mail: jacob@zedat.fu-berlin.de

The author would like to thank
Corinna Fischer, Annette Piening, Martin Cames,
Kerstin Tews, Katja Schumacher and Klaus Rennings
for valuable comments on earlier versions of this paper.

The publication is based on a research project
funded by the German Ministry of Education and Research,
grant number 07RIW1A.

ISSN 1612-3026
FFU-rep 10-2003

FORSCHUNGSSTELLE FÜR UMWELTPOLITIK
Freie Universität Berlin
Fachbereich Politik- und Sozialwissenschaften
Otto-Suhr-Institut für Politikwissenschaft

Ihnestr. 22
14195 Berlin

telefon +49-30-838 566 87
fax +49-30-838 566 85
email ffu@zedat.fu-berlin.de
internet www.fu-berlin.de/ffu/

Contents

List of figures

List of tables

Summary

In the paper it is analysed which countries are likely to become the lead markets for fuel cells in stationary applications. The study is part of a larger research project "Policy Frameworks for the Development of International Markets for Innovations of a Sustainable Economy - from Pilot Markets to Lead Markets (LEAD)". In the course of this project more than 20 environmental technologies were examined regarding the regional differences of their market introduction and penetration. The project aims to explain why some countries are earlier in the introduction of environmental innovations and why the market penetration is more encompassing than in others. If the technologies of the pioneering countries diffuse to other countries without great modification, they can be analysed as lead markets for environmental innovations.

Fuel cells for electricity generation in stationary are an emerging technology that is still in the stage of development and demonstration. There are several competing innovation designs on the market, and it is still open which technology is likely to be successful. The different technologies are described and compared among each other, as well as against conventional technologies for power generation.

Three countries can be identified as front-runners in the development of fuel cells, namely the United States, Japan and Germany. These countries are analysed regarding the R&D policies, the conditions for combined heat and power generation (CHP), the structure of energy prices, and regarding environmental policies that aim at internalising the environmental costs of energy production. The paper evaluates the different activities to stimulate the development and market introduction of fuel cells from a comparative perspective in order to assess respective lead market potential.

1 Lead markets for fuel cells in stationary applications

As part of the research project "Policy Frameworks for the Development of International Markets for Innovations of a Sustainable Economy - from Pilot Markets to Lead Markets (LEAD)" more than 20 environmental technologies were examined regarding the regional differences of their market introduction and penetration (see Beise, Blazejczak et al. 2003 for a comprehensive overview on the project). The core question is: Why are some countries earlier than others in the introduction of environmental innovations? The studied technologies include, among others, energy technologies such as photovoltaic, wind energy, fuel cells for stationary energy generation, chemicals such as substitutes for CFCs, cadmium, phosphate in detergents, automobile technologies, e.g. energy efficient motors, catalytic converters for exhaust gas, fuel cells for mobile applications etc. We studied both historical cases of innovation and diffusion as well as ongoing processes.

There are considerable differences in the rate of adaptation of innovations among different countries. Some countries are earlier in innovation and market penetration is more encompassing than in others. If the same innovations are adopted subsequently without great changes in other countries, the countries where the first market introduction took place can be characterised as lead markets. The concept of lead markets has been developed and fruitfully applied for non-environmental innovations. Examples of lead markets for such technologies are mobile phones in Finland, the fax in Japan or the internet in the USA (Beise 2001). These markets are characterised by the fact that product or process innovations that are designed to meet local demand preferences and conditions can be introduced and successfully commercialised without many modifications in other regions as well. The country of origin of an innovation can be defined as the core of the world market where local users are early adopters of a technology that later diffuses on international scale (Beise 1999).

Our studies reveal, that there are many examples of lead markets for environmental innovations as well. The history of environmental protection is rich in examples for lead markets: it encompasses the legally enforced introduction of catalytic converters for automobiles in the United States, desulphurization technologies in Japan, the Danish support for wind energy or the CFC free refrigerator in Germany. Another example is the global diffusion of chlorine-free paper, from the political activities by Greenpeace and the EPA in the United States, via the introduction of chlorine-free paper whitener in Scandinavian countries and various Greenpeace campaigns in Germany and Austria, right through to effective political market intervention in Southeast Asian countries like Thailand. By this campaigning of Greenpeace environmental friendlier technologies for paper production diffused worldwide (Mol and Sonnenfeld 2000, Beise, Blazejczak et al. 2003). The latter case shows that political action that stimulates internationally successful innovations is not limited to governmental agencies only, but that this function at least regarding the process of setting environmental objectives may be taken over by environmentalists.

Lead markets can be depicted by comparing the rate of market penetration in the different countries. Diffusion of environmental innovations starts earlier in the leading countries and market penetration is typically more encompassing than in other countries. What are the determinants that cause the differences in the introduction of innovations? What are the characteristics of the leading countries? Is there room for manoeuvre for a intentional establishment of lead markets for environmental innovations?

From our case studies as well as from previous studies we can infer that environmental innovations have to be largely ascribed to governmental (or – however less frequent – to NGO) activities. Environmental innovations are not only stimulated by surpassing environmental consumers preferences in a given country, but also by special promotional measures, or by political intervention in the market (Klemmer, Lehr et al. 1999; Jänicke, Blazejczak et al. 2000). In case of end-of-pipe technologies which require additional costs without improving the benefits for the users, regulatory interventions are even indispensable for innovation and diffusion. But also in cases of integrated technologies, with additional advantages in efficiency, policy measures are necessary to stimulate innovation and to support diffusion. The under-investment in environmental innovation can be explained by the double externality of R&D efforts spent in environmental technologies: Alongside the spill-over effects that can be observed for any R&D activities, efforts in *environmental* technologies do result in improvement of the environment which again is a public good (Rennings 2000).

Environmental innovations do have another peculiarity that is in turn in favour for their international diffusion: They provide marketable solutions to environmental problems that are usually encountered world-wide, or at least in many countries. Thus, technological solutions to environmental problems inherently lend themselves to adoption in international or global markets.

The specifics of environmental innovations are not able to explain the regional differences in adoption and diffusion of innovations. For this, the framework conditions and political strategies in the leading countries have to be analysed. The dependency of environmental technologies on regulatory measures leads to the question in how far national environmental policies aiming to stimulate lead markets remain possible and effective in the context of globalisation.

The analysis of factors that determine a leading position of a country with respect to a technology should not stop with an ex-post evaluation. The crucial question is, in how far a lead market may be identified in the emerging stage of a technology. This paper discusses the example of fuel cells for stationary applications as an emerging market. In the following the different technologies are described and compared to each other as well as to conventional technologies for power production. The different fuel cell technologies can be understood as variations in the innovation design. Countries that are early in the development and adoption of innovation designs that later prove to be successful on the world market do have advantages as lead countries. Therefore, for each of the technologies that are under development today, it is analysed which countries and firms are the frontrunner.

Based on a literature survey, several factors are identified that are expected to be in favour of the development and market introduction. Among these are favourable conditions for combined heat and power generation (CHP), a favourable structure of energy prices, ambitious environmental policies that aim at internalising the environmental costs of energy production. In a next step, the policy programmes and framework conditions in the leading countries USA, Japan and Germany are compared and analysed on this background. It is particularly focused on the patenting activities, as well as the governmental funding for research and development of fuel cells in a comparative perspective in order to identify countries with advantages in R&D. The framework conditions for CHP technologies are analysed for each of the country. In respect of policies that support the introduction of fuel cells, special attention is given to the question in how far different sectors of policy making are coordinating their activities. In all of the countries, relevant policies are developed by the departments of the environment, industry, energy, and in the USA also by the department of defence. Finally, the paper tries to assess the different activities to stimulate the development and market introduction of fuel cells from a comparative perspective in order to assess respective lead market potential.

2 Innovation designs

The principle of the fuel cell was already demonstrated by W.R. Grove in 1839. This technology started to be developed only around 1950, first in England, then also in Germany and the USA. This research was the basis for a NASA development program that first applied fuel cells in the Gemini Program (1961) and in the Apollo Mission (Oertel and Fleischer 2000). Fuel cells produce electricity without needing the detour using thermal energy. They are, like batteries, electro-chemical devices. The preferred fuel is hydrogen; due to its high reactivity the need for (expensive) catalysts is minimized. At present however, hydrogen is reformed from natural gas (which is a process that diminishes the environmental advantages of fuel cells since CO_2 and NOx is released). The common oxidation chemical is atmospheric oxygen, due to its ubiquitous availability.

Fuel cells can be applied very differently, for supplying individual electronic machines, or for powering of automobiles, heating and electricity supply in individual homes, and in stationary power stations of different sizes in the industrial and public energy supply. This case study concentrates on the partial market of fuel cells for stationary power generation combined with the utilization of heat; as part of the same project, a further case study of the ZEW (Rennings and Beise 2003) is analyzing the evolving market for mobile applications in the area for cars. Due to capacity reasons, the partial market for fuel cells that supply heat and electricity to homes had to be left out.

In contrast to conventional power stations fuel cells have a high efficiency factor, even in the partial load area. The electrical efficiency factor is at around 40%, the overall efficiency factor when using thermal energy can be up to 80%. Another advantage is that there are virtually no NOx and SO2 emissions and that the machines are very quiet. The introduction of this technology is also closely connected to the hope that environmental advantages can be realized when compared to conventional power stations. Furthermore, they are seen as being a bridging or transitional technology for the introduction of hydrogen-based energy systems, synthesized with the help of solar energy.

In the last few years, the first efforts aiming at a commercialization of fuel cells were undertaken mainly in Japan and in the USA. Here PAFC fuel cells were used (these models are described in more detail below). Research and development efforts as well as first demonstration installations will also lead to further advances with other models.

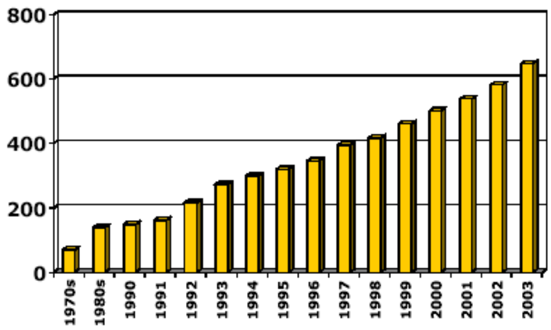
Fuel cells are classified by the type of electrolytes used, as well as the by processing temperature. Commercial chances are given to the 4 types that are introduced below (Phosphoric Acid Fuel Cells (PAFC), Proton Electrolyte Membrane Fuel Cells (PEFC), Molton Carbonate Fuel Cells (MCFC) and Solid Oxide Fuel Cells (SOFC)). The various cell types differ according to the operational temperature and the requirements for fuel pureness. Regarding the requirements for the fuel MCFC and SOFC cells have a advantages compared to the PAFC and PEM cells. Not portrayed are the Direct Methanol Fuel Cells (DMFC) that can be used for small consumers as well as in mobile applications up to about 50 kW and the Alkaline Fuel Cell (AFC) that had its first use in space projects but also has special requirements when it comes to fuel pureness. The further development of this cell type was stopped (Hirschenhofer, Stauffer et al. 1998).

A variety of different industrial sectors is taking part in the development and the manufacturing of fuel cells; these are chemistry (membranes, gaskets), ceramics (membrane, electrodes), catalysts, metal/carbon (bi-polar plates, corrosion protective films), process technology (heat exchangers, compressors, amongst others), electrical engineering, mechanical engineering, power installation construction (cell stacks, systems) and the electronics industry (portable applications).

Even though there were comprehensive research and development activities going on in these industrial sectors, it seems unrealistic that market forces alone will be able to force a large-scale introduction and use of fuel cells. Conventional technology for energy conversion has been tested and is available; the fuels for heat and power generation for these technologies are relatively cheap. Without further incentives or dramatic changes in the availability of fossil fuels, it cannot be expected that investments will be made into the barely even tested fuel cell technology (Department of Energy 2003). The main barriers are the high costs and risks that have to be taken to reduce the costs of this technology to a competitive level compared to conventional technologies.

For the industrial and public power supply that is being discussed here, it seems that high temperature fuel cells (MCFC and SOFC) are most suitable. These, though, are still in the early stages of development. Their performance spectrum ranges from capacities with few kW to several MW thereby covering micro gas turbines and motor CHPs all the way to combined cycle power stations. Since the start of development in the 1960s there are now 650 stationary systems installed globally with an output level of over 10 kW each. As much as 65 of these were installed in 2003 (Cropper, Geiger et al. 2003).

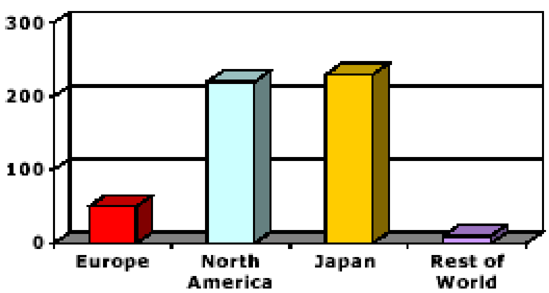
Figure 1: Cumulative Number Stationary Fuel Cells > 10 kW



Source: Cropper 2003

Most facilities, according to this source, can be found in Japan, closely followed by North America. In Japan research and testing has been strongly supported by government agencies since the early 1980s. The gas companies of Tokyo and Osaka have installed the world's largest demonstration units.

Figure 2: Regions of Operation



Source: Cropper 2002

Most of the installed units, are US made units described in more detail below. They have been constructed and sold since the start of the 1990s as a limited series. In the USA the market launch was supported by a subsidy program launched by the Department of Defense (DoD).

Fuel cells compete with established technologies, e.g. gas and steam combined cycle gas turbines (CCGT) cogeneration plants, that have an equal efficiency at least in the full load area and are meeting existing emission standards. In the low output sector motor-driven combined heat and power plants (CHPs based on internal combustion engine) are already on the market and micro-turbines are being developed. In order to be able to compete against these technologies, the price for fuel cells must be greatly reduced and long operation times must be proven. The German Federal Ministry of Economics (BMWi 2001, p. 47), responsible for energy policy, can be quoted with a requirement of €1250/kWel and 40,000 hours of operational use of fuel cells to become competitive compared to conventional energy technologies.

As with all CHP technology, assumptions regarding competitive prices for the installations strongly depend upon the expected electricity credit given. Due to deregulation, the decrease in electricity prices reduce the incentive to invest in CHP installations, thereby also in fuel cells.

In the following, the different technologies that are actually applied for stationary power production are briefly described in particular regarding their market potential and the companies that focus on their development and market introduction. These technologies represent the different innovation designs. It remains an open question, which of these innovation designs will successfully compete against conventional energy technologies. The development activities vary in the countries in respect to the different technologies. Hence, countries that are able to concentrate on technologies that are successful on the market later, have advantages as lead markets. Therefore, as a first step a brief description of the technologies is given as well as an overview on the main companies that are involved in their development.

2.1 Phosphoric Acid Fuel Cell (PAFC)

For stationary use, the development of Phosphoric Acid Fuel Cell (PAFC) started in the 1970s and installations designed on the basis of this technology have been commercially on sale since 1992 (Oertel and Fleischer 2000, p. 31; Brown and Jones 1999, p. iv). Up to recently, the US company ONSI had a ready-to-be-connected module PC25C on sale with an output performance of 200 kWel. Additional companies that will have similar technologies on offer in the future are Fuji, Mitsubishi and Toshiba. At the moment the latter are concentrating on the Japanese market. According to other sources, Japan is even leading the use of such technology (BMWi 2001, p. 44, BINE 2000). However, most of the installed units are of the US made type. All in all, 200 units of this type were set up globally; of which about half are still in operation. The installations were taken off the grid after a mean lifetime of 30,000 operational hours. During their lifetime, the electrical efficiency factor sank from 40% to 30-35% (Simader and Heissenberger 1999, p. 26). In Germany alone, 15 units were installed, of which 10 are still in operation. 30 units were installed and put into operation in the US military sector. The disadvantages that are stressed are that investment costs are higher than with conventional motor CHP and that starting the utilities is a complex and time consuming task and therefore this technology is appropriate only for base load operation (Simader and Heissenberger 1999, p. 24 f.). Investment costs are stated as being USD 3000/kW (Department of Defense 1998, p. 3). By manufacturing in mass production a reduction to about $1300/kW is thought possible (Dienhart, Nitsch et al. 1998; Brown and Jones 1999).

Another disadvantage is that the installations have to be kept at a temperature of between 40-50°C even when idle in order to avoid an over-crystallisation of the electrolyte (BINE 2000). Furthermore, special requirements have to be adhered to vis-à-vis the nitrogen concentration of the gases used (BMWi 2001, p. 44).

In Japan, Fuji has PAFC units commercially on offer since the end of the 1990s and they were realized as CHP installations repeatedly in the past decade. In the recent past, additional installations have been constructed that use biogas as a fuel (Homma 2000). In India the development of a stack by Bharat Heavy Electric has been underway since the end of the 1980s (Cropper 2002). Proton-electrolyte-membrane fuel cells (PEFC, PEM) Proton-electrolyte-membrane fuel cells (PEFC, PEM) fuel cells were first developed in the 1960s; the reliability however was much lower than that of alkaline cells[1]. Only in the 1990s new impulses were provided with the introduction of new membrane types (Oertel and Fleischer 2000, p. 31). In contrast to the high temperature cells described below, the low processing temperatures of about 80°C allow for, a swift

[1] Alkaline fuel cells have been the first cell type; they were developed for application in spaceships by the NASA and were used in the Gemini program in the early 1960s for the first time.

operational start of the cell and quick load changes. The cell type is especially suitable for mobile applications as well as for small home units. Additionally, there are developments in the capacity range of more than 100 kW. With the considerable cost pressure on fuel cells in mobile applications there is also the hope that, for this type, larger cost cutting potential can be achieved for stationary applications (Theenhaus and Bonhoff 1999).

The low operational temperature does have the disadvantage that no processing steam can be won. A cost cutting potential is seen to be the reduction of the used platinum (BINE 2000). The CO content in the used fuel has to be limited to 10-20 ppm, a higher concentration would destroy the cells (BINE 2000). In order to stay within this limit, the hydrogen won from the reformation process has to be cleaned of CO.

PEFC and PEM with a size of 250 kWel are currently being tested in Canada/Vancouver by the company Ballard as well as in Berlin by the BEWAG, in the latter case supported by European research funds from the program THERMIE (Oertel and Fleischer 2000, p. 22). The costs for this installation are quoted as being USD 8000/kW (Lievonen, Císcar et al. 2000, p. 65). The installation was delivered by the Canadian firm Alstom-Ballard. Of the total costs of ca. USD 3.5 million 40% are financed by EU funds, 10% by Alstom and the remaining 50% by the participating electricity supply companies (Bewag, EdF, HEW, PreussenElektra and VEAG). Three further units of this type were planned in the years 2000 and 2001 for the Netherlands, Switzerland and Belgium (Pokojski 2000, p. 399).

Ballard has been testing units with a capacity of 250 kW since 1997 and is planning the development of cells with a performance output of between 100 W and up to 1 MW. Other companies that are active in this technology sector are Analytic Power, Avista Labs, H Power, Plug Power, and Northwest Power Systems. The market launch of fuel cells that supply homes was expected in the near future (Brown and Jones 1999, p. 12), the commercial sale of the 250 kW power stations was announced in 1998 for the year 2002 (Hirschenhofer, Stauffer et al. 1998, p. 1-15).

In 1998 the companies Alstom and Ballard announced the construction of a PEFC fuel cell plant in Dresden for the year 2000. There the 250 kW unit that was tested in Berlin was supposed to be produced in series. This decision has been deferred to the year 2004.

Apart from the use in the mobile sector and in the already mentioned stationary applications, these fuel cells, developed by Siemens, are also in operation in submarines (Department of Defense 1998, p. 3). In Japan PEFCs with very low capacities are being tested in the supply of homes (Homma 2000).

2.2 Molton Carbonate Fuel Cells (MCFC)

For this cell type a commercial market launch is expected first, right after the PAFCs. That is why they are also described as fuel cells of the second generation. The operational temperature of MCFCs is around 600-650°C. Therefore, the heat generated can be used for the reformation of the fuel. Furthermore, expensive catalysts are omitted and the requirements for the pureness of the fuel being burned are lower.

In the USA the Energy Research Corporation (ECR) and MC-Power are working on the commercialization; in Europe and Japan several companies are pursuing the development of this technology: Brandstofel Nederland, Deutsche Aerospace and Ansaldo (Italy); MTU Friedrichshafen, Hitachi, Ishikawajima-Harima Heavy Industries, Mitsubishi Electric Corporation and Toshiba Corporation. In 2003 a joint venture of MTU with the German utility RWE was founded, that aims at starting a MCFC series production in 2006.

In the USA the companies Energy Research Cooperation (ERC) and MC-Power have realized demonstration projects with a capacity of 250 kWel - 1MWel. In Germany there is a unit with a capacity of 280 kWel capacity that the MTU tested in the years 1997-98 in Dorsten as contract work for Ruhrgas. The Stadtwerke Bielefeld started with the operation of a demonstration unit in the year 1999 (BINE 2000). Another unit in a hospital was started in 2001 and seven further installations have been announced for 2003/04 (Cropper 2002). The unit, developed by MTU, is supposed to radically reduce the costs by integrating the system elements in a single casing. The costs are expected to be EUR 1200/kW. (http://www.h2guide.de/projekte/pfs12.html from 2.8.02). MTU is connected to the US company Energy Research Corp. (nowadays Fuel Cell Energy) by a licensing agreement. This company operated a 2 MW unit in Santa Clara, CA, during the years 1996 - 1997 (BINE 2000, Brown and Jones 1999, p. 18; Hirschenhofer, Stauffer et al. 1998, pp. 1-16). In spite of a variety of problems arising of operating the unit, the company is planning a 2.8 MW installation with the same technology. The company is also participating, in cooperation with MTU, in a 300 kW MCFC unit in Friedrichshafen.

Fuel Cell Energy is developing a commercial unit with a performance of 250 kW and already has a production capacity of 50 MW/a in the USA at its disposal. By 2004, 1.5-3 MW units are also supposed to be available (Cropper 2002).

In Japan several demonstration installations have been set up, including a 1 MW unit in the year 1995 that was in operation until 2000. MITI and Nedo are planning further demonstration units in order to support the commercialization process (Homma 2000). The development was pursued by the company IHI that has announced two 300 kW installations for the year 2002 (Cropper 2002) that is, however, still under development (Masaaki, Nobuyuki et al. 2003). Further units with a performance range of 75 kW to 1 MW are planned in Japan and the USA (Hirschenhofer, Stauffer et al. 1998, p. 1-17).

The Italian firm Ansaldo is developing MCFC units with sizes ranging from 100 kW to 30 MW. The market launch of a 500 kW unit as well as a several MW unit is scheduled for the year 2005 (Cropper 2002).

In comparison to PAFC and PEFC cells, MCFC have advantages regarding the CO content of the fuel (CO is even used for the process in the MCFC procedure) and the higher process temperatures that facilitate the use of heat energy, e.g. as process steam. The disadvantage, though, is that the heating-up procedure takes several days and that special safety measures are necessary because of the highly corrosive carbonate smelt (BINE 2000). In comparison to SOFC cells, described below, cheap material can be used for MCFC.

2.3 Solid Oxide Fuel Cells (SOFC)

The technological development of this cell type is being undertaken in the USA by Siemens-Westinghouse, AlliedSignals, SOFCo, Technology Management and Ztek. In Europe there are 8 companies, in Japan 7 and one is in Australia (Hirschenhofer, Stauffer et al. 1998, p. 5-1). Siemens-Westinghouse is seen to be the farthest.

The working temperature of SOFC can be up to 1000°C and allows for an installation concept with integrated reformation and a flow-operated gas turbine. In comparison to MCFC there are no problems with corrosive materials. SOFC units are planned in the sizes 60-70 MWel by Siemens-Westinghouse. The worldwide first prototype was set up 1998 in Arnhem (NL) with a performance level of 100 kWel (BINE 2000; Simader and Heissenberger 1999, p. 30) and was moved to Essen (GER) after a three year period of operation (Siemens 2002). A 220 kW Siemens unit was put into operation in California. A 320 kW unit for RWE and a 1 MW unit for EnBW and EdF were planned for 2001 and 2002 (BINE 2000). These planned installations, just as the one in California, are equipped with a flow-operated gas turbine. A commercial 250 kW unit is planned by Siemens-Westinghouse for 2003.

The British company Rolls-Royce has been active in the development of SOFCs since 1992 and is working on a unit that combines an 800 kW SOFC with a 200 kW gas turbine. A prototype is planned for 2004, the commercial launch for 2005/06 (Cropper 2002).

In Japan a trial unit with a capacity of 15 kW that has been developed by Mitsubishi and Chubu Electric Power is currently in operation. Both companies are planning a commercial launch in the year 2004 (Homma 2000; Cropper 2002). Another Japanese company, Electric Power Development, is working on a 100 kW installation.

Concerning the electrical efficiency factor of about 50% (resp. 60% when combined with a turbine), SOFC power stations are comparable to conventional CCGT plants with a performance of 100 MW (electrical efficiency about 53%). An advantage, though, is that this efficiency factor can already be reached in the smaller units (from 100 kW onwards) and in the partial load operation, whereas smaller conventional installations of about 1 MW only show an electrical efficiency factor of 40%. In addition, separating the CO_2 in the SOFC units is comparably simple as no mixing with the oxygen and nitrogen in the air takes place. Therefore carbon sequestration can be carried out much easier (Stimmig, Rzepka et al. 2000, p. 13). Furthermore, the emission of classic air pollutants by SOFCs is much lower so that one can speak about “near zero emission” in this case (Stimmig, Rzepka et al. 2000, p. 15).

Also for these installations a longer heating-up time is necessary. The high temperatures impose high requirements on the used material (BINE 2000). Regarding the projected costs and the efficiency, SOFC cells are comparable with MCFC cells. An advantage of SOFC cells is above all when they are combined with a CCGT power station as is foreseen because of their higher electricity efficiency (Brown and Jones 1999, p. 25). However, such a combination is also being developed by Fuel Cell Energy for MCFC cells. Furthermore, SOFC cells, just like PEFC installations, though not MCFC or PAFC, are being tested in very small units.

A 1 MW unit that is planned by Siemens/Westinghouse combines a SOFC fuel cell with a gas turbine. Thereby the fuel cell replaces the furnace of a CCGT plant. With this unit, an electrical efficiency factor of 60% is expected (Hirschenhofer, Stauffer et al. 1998, p. 1-18). In the long term perspective (until 2015), installations with a performance range of 50-60 MW are planned (Simader and Heissenberger 1999, p. 30).

A test unit of a hybrid installation with a performance level of 220 kW was put into operation in the year 2000 in the USA. The electrical efficiency was stated as being 57% (Cirkel 2000, p. 90).

A further development direction by Siemens-Westinghouse is a “zero emission unit” for which the CO_2 created is sequestered and stored in exploited oil fields. This technology is being developed together with Shell (Cirkel 2000, p. 91).

The Siemens-Westinghouse unit is supposed to cost USD 1500/kW (Lievonen, Císcar et al. 2000, p. 65). The stack alone is quoted with USD 700/kW, the material costs, however, are only USD 7-15/kW. The major share is constituted by the assembly costs. This hints to a large cost-cutting potential (Hirschenhofer, Stauffer et al. 1998, p. 5-11).

In the framework of the US government’s industry initiative SECA, the development of a commercial 5 kW SOFC is being strived for, one that can be applied in a variety of sectors. By combining several stacks, power stations that have a size of several hundred kWs can be planned. Through such a standardized cell for a variety of applications, competitive prices for the cells are expected to be reached a lot sooner.

2.4 Comparison of the Fuel Cell Types

Brown and Jones (1999, p. iv) compare the characteristics of the different cell types that can be considered for use in stationary units (table 1). At the same time assumptions on the prices and availability differ considerably from other sources.

High temperature cells have several advantages: firstly, demands regarding the fuel purity are low (with the exception of pollution by sulphur), secondly, a reform process for the separation of hydrogen out of the respective fuel can be dispensed with as the operational temperatures allow for an internal reform process, and thirdly, demands of the catalysts being used are lower. Whereas with PEFC and PAFC platinum is used, for MCFC nickel is used and with SOFC perovskite, a substance family that describe ceramic crystals. These catalysts are much cheaper than platinum. A disadvantage, however, is the complex cell design and the higher maintenance requirements (Hirschenhofer, Stauffer et al. 1998: p. 1-5). The reliability of high temperature cells during continuous operation could not be demonstrated up to now. The development status is restricted to pilot units.

Table 1: Comparison of Fuel Cell Technologies

Characteristics	Fuel Cell Types			
	PAFC	PEFC	MCFC	SOFC
Current development stage	Series	R&D	R&D	R&D
Begin of commercialization	1992	2001	2002	2003
Market maturity	2005+	2005+	2005+	2005+
Expected installation costs USD/kW	1500	1300	1300	1300
Costs for the replacement of the stacks (USD/kW)	360	220	430	400
Lifetime of the stacks (hours)	60,000	40,000	50,000	40,000
Fixed operational costs per year and USD/kW	30	30	8	20
Variable operational costs USD/MWh	1.4	1.4	2.0	2.5
Electrical efficiency factor (%)	37	36	52	63
Total efficiency factor	73	70	82	77
Usable temperature °F	250	160	1050	400
Annual availability (%)	97	96	95	86

(Brown and Jones 1999, p. iv).

Up to now, about 80% of the installed fuel cell facilities are based on PAFC technology. However, in 2003 most of the installed systems were based on MCFC technology (ca. 40%), followed by PAFC with ca. 35% and PEMFC with 20% (Cropper, Geiger et al. 2003).

It remains, however unclear which of the technologies will be actually successful in competition with conventional energy technologies. The PAFC technology seems to be outdated and the recent overtaking of MCFC installations seems to prove this assumption. Regarding stationary applications the high temperature technologies MCFC and SOFC have advantages regarding the usable heat. However, PEM fuel cells might achieve more comprehensive learning and scale effects because of their utilization in mobile applications.

2.5 Comparison of the costs to conventional energy technologies

Fuel cells are under high cost pressure as they, when compared to existing technology (combustion engine, conventional power stations, etc.), promise little or no additional value – the generated electricity has the same quality like from conventional generation. It is only if there are major changes in the framework conditions for conventional technologies in terms of stricter emission standards, that fuel cells may gain considerable advantages. Therefore, fuel cells are a substitute product. Other advantages include the marginally higher fuel efficiency, the slightly higher share of output of electricity, and an efficiency level, that is largely independent from the work load and the power station size, the possibility to use a variety of fuels. A disadvantage is the substantial investment costs.

Padró and Putsche (1999) compare investment costs and power production costs for different fuel cell technologies based on a literature analysis. The research is based on a variety of installation sizes ranging from a few kW to up to 100 MW. Accordingly, for SOFC and MCFC fuel cell system costs of USD 600-1000 are expected. For stationary PEMFC or PAFC units, however, higher costs (USD 1000-2500) are generally expected. Power production costs are calculated to be USD 0.06 – USD 0.13 per kWh (pp. 17-22).

There are, however, some niche markets already today for which the higher installation costs seem to be acceptable already today. These are mainly applications for which a high reliability of electricity service is required. Due to the few moving parts fuel cells are expected to be a highly reliable technology, however, apart from PAFC the long term reliability has not been proven yet (Pehnt and Ramesohl 2003).

Furthermore, a considerable rise in the share of decentralized power generation is expected. Pehnt and Ramesohl (2003) quote a study of Allied Business Intelligence which expect a rise from now 20 GW to 280 GW–350 GW world-wide in 2011. Another market survey of the German based utility RWE predicts a share of 30% of electricity produced by distributed power in Germany in 2015 of which a considerable share is likely to be provided by fuel cells.

2.6 Comparison of Environmental Impacts

Dienhart et al (1998) compare a PEFC fuel cell with a motor-powered CHP and arrived at the result that the fuel saving value, depending on the system compared, is between 5 and 15%. In comparison to motor CHPs as well as production that is uncoupled to the power net, fuel cells show the lowest value in nearly all air pollutant categories. According to the calculated example given by the authors, in order to reach the comparative electricity price of a motor-driven CHP plant, the investment costs should not be above about EUR 850/kW. All in all, the authors claim that the ecological advantages of fuel cells in relation to motor-driven CHPs are not clear enough in order for a replacement to take place. The cost reduction potential, though, for motor-driven CHPs is seen as being pretty much exhausted (Bünger 2000).

In contrast, a study by the US Department of Energy (Department of Energy 2003: p. 5) highlights the environmental advantages. Here, however, fuel cell power stations are compared to the currently run coal, gas and oil power stations. In comparison to an average US power station, a natural gas run PAFC fuel cell emits only 0,2% of classic air pollutants. The CO_2 emissions are quoted as being about 40% of the emissions of conventional power stations.

In a more extensive comparison of conventional technologies with high temperature fuel cells, Dienhart et al. (2000) conclude that fuel cells have advantages when it comes to the electrical efficiency factor, the combined heat and power (CHP) coefficient, the partial load behavior, the environmental effects, availability and – at least potentially – with regard to the maintenance expenditures and load change speed. The disadvantages of fuel cells are that dual fuel operation (gas and heating oil) is not possible and the operational starting time is a considerable longer and much more costly after longer periods of shut-down. However, the overall efficiency factor during combined heat and power (CHP) operation and the temperature level of the processing heat are comparable. The competitive investment costs for the module (without the connection) are quoted as being EUR 700-1050/kW. The fuel saving has a positive effect, the negative side is the fact that the stacks have to be replaced after about 5 years. The market in Germany for decentralized CHP installations within a performance range of 0,1-10 MW is around 500 MW/a. Export markets may eventually be established with the EU's objective of doubling of the CHP level from currently 9 to 18%. In the medium term the integration within coal power stations could represent a further new market segment. With the upcoming age-related replacement investments for power stations with a volume of 30,000 MWel up to 2010 in Germany, fuel cell systems could also profit from the promotion of CHPs (e.g. by obligatory quotas for CHP). However, a decentralization of power production does not necessarily have to rely on fuel cells; this can also be achieved with conventional power stations.

Fritsche (1999) compares different fuel cell types with conventional CHPs of different sizes and a fuel cell power station with regard to emitted pollutants per 2 kWh thermal output and 1 kWh electrical output. The comparative standard therefore takes account of the higher heat level of conventional power stations. The author comes to the conclusion that fuel cells have the lowest level for all emitted “classic” pollutants. Concerning CO_2 , fuel cells are a bit behind (5-10%) the emissions of CHPs. All in all, this study sees no clear advantage for fuel cells; the much lower air pollutants though could be an advantage in areas heavily affected by this problem. The economic advantage of fuel cell power stations would only be given when the emission standards set for conventional power stations are tightened and therefore the operating costs made more expensive (Dienhart, Pehnt et al. 2000). Furthermore, fuel cells that are powered by pure hydrogen that in turn is produced by renewable energies has virtually no emissions.

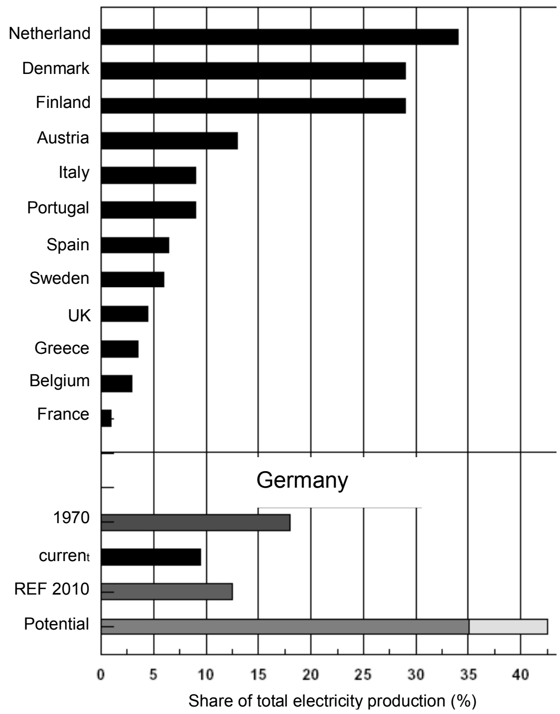
2.7 Market for CHP Installations

The following illustration (see figure 3) gives an overview of the percentage of CHP-produced electricity in the mid 1990s in Europe, which at the same time represents the market potential for the fuel cells discussed here .

The most promising markets for decentralized CHP installations are expected in Germany. These are accounted for with 2,700 units with a capacity ranging from 5 kWel to 4 MWel, totaling to a capacity of 1450 MWel (that is 1,2 % of the overall capacity for electricity generation) and a growth of 250 MW/a (Nitsch and Dienhart 1998). Pehnt and Ramesohl (2003) quote scenarios of up to 50 GWel for domestic CHP utilities until 2020 in the EU-15 countries and a total of 190 GWel. However, the situation has changed dramatically after the liberalization of electricity markets that lead to a decline in investments. The future of investments in CHP technologies remains unclear.

Whether fuel cells succeed in taking over a larger market share depends on the investment costs. The competitive costs of € 700-1050/kW quoted in several studies are still relatively far away from the current prices.

Figure 3: Electricity generation from CHP plants

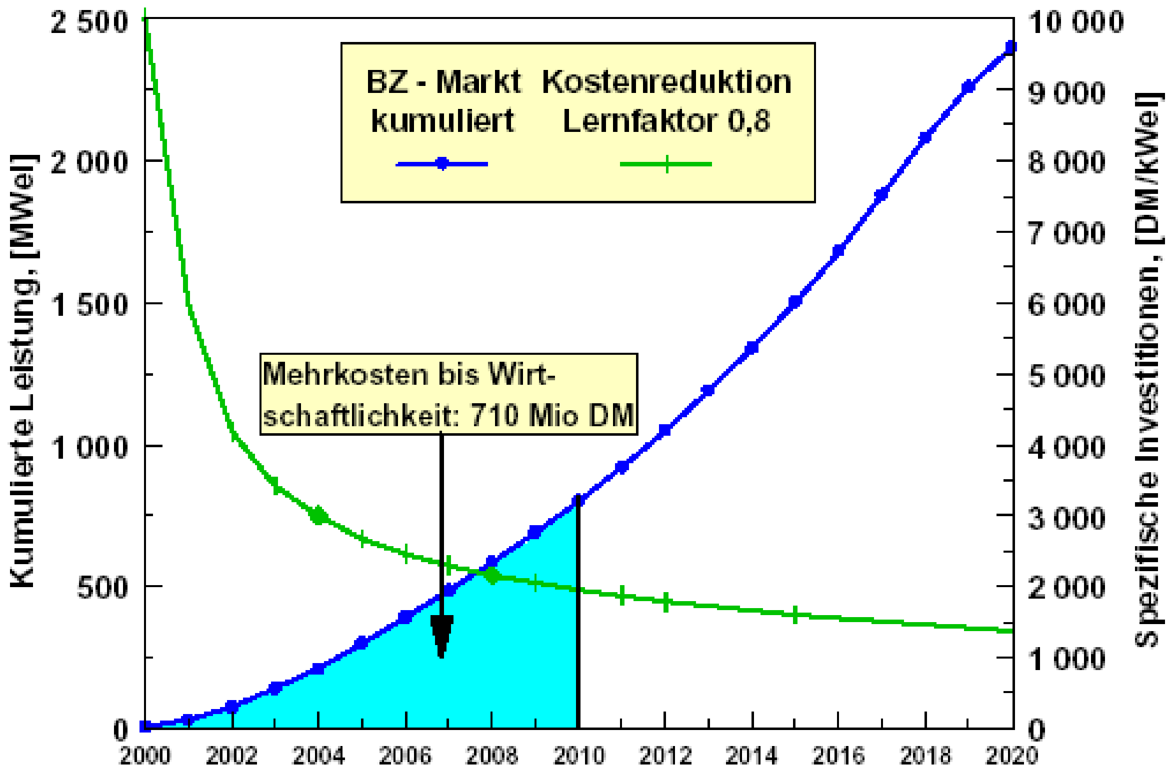


Source: Nitsch and Dienhart 1998

The only PAFC unit worth mentioning (in terms of output figures) costs USD 3000/kW, the Berlin PEFC is listed with USD/€ 8000, the Siemens-Westinghouse SOFC unit was announced with USD 1500/kW. However, considerable learning effects during the early diffusion phase can be expected. Based on experiences with other energy technologies a learning factor of between 0.75 and 0.9 can be assumed (Birnbaum, Dienhart et al. 1999).

Based on these target values and parameters Pehnt and Nitsch (2000) judge that in order to reach EUR 1,000/kWel, a starting point with a series production of EUR 5,000/kWel must be assumed, as well as an installed capacity of 5 MWel at the start of series manufacturing. Furthermore, a cumulative performance level of 700 MW is necessary in order to reach the given target value.

Figure 4: Expected learning curve fuel cells



Source: Birnbaum, Dienhart et al. 1999, p. 86

3 Political Instruments

A variety of framework conditions influence the adoption of the fuel cell (Stolten and Höhlein 2000; Department of Energy 2003, Bünger 2000; Birnbaum, Dienhart et al. 1999, Pehnt and Ramesohl 2003). These can be differentiated in terms of, first, the factors that can be influenced by political measures and secondly the relatively static economic and regulatory frameworks:

Political measures in favor of fuel cell introduction framework:

- At the current stage of fuel cell development, that is largely still in the R&D phase, incentives for potential users are called for, as for example subsidizing demonstration projects. Furthermore, it is called for further promotion of basic research, especially the reduction of cost risks for privately funded research. In order to achieve a signal effect that motivates private actors to invest in the development of fuel cells, long-term political measures are said to be necessary as well as the coherence of the measures of different policy sectors. Energy, environmental and industrial policy makers should not send out confusing and contradictory signals. The difficult phase of the market launch can be overcome through public procurement, thereby involving a range of different state actors. R&D activities should be supported by the inclusion of fuel cell technology in training courses at a university level.
- When it comes to the market introduction, it is called for strategies that provide a stabilization of the market prospects for fuel cell generated power. Important factors in this respect is the political framework for CHP in general, e.g. emission standards for CHP installations, measures for the support and promotion of CHPs and tax breaks for fuels and the infrastructure for heat usage. The conditions for CHP production are however still marred by uncertainty in most countries. Important in this respect are non discriminatory rules for third party access to the power grid, i.e. clear, legally secured rules for the feed-in of surplus electricity and for the purchase of reserve and balancing power. The market introduction can be furthered by subsidizing the prices for fuel cell generated electricity very much alike for power from renewable sources. A frequent topic in the literature is the need to simplify existing regulations (e.g. training and allowing craftsmen to connect the gas as well as electric systems), just as it is necessary to harmonize this on a European level in order to allow for the export of the technology. This is also valid for fuel and safety standards. Furthermore, setting standards and norms for the operation of fuel cells is necessary in order to minimize possible liability risks.
- Finally, the chances of fuel cells depend on the framework conditions for conventional energy technologies. If environmental policies lead to an internalization of environmental costs caused by energy production, the allowable investment costs for fuel cells are higher. However, since the costs of fuel cells are today 2 to 10 times higher than conventional technologies, it seems unrealistic that such strict measures are applied which bring the costs of conventional technologies on a comparable level. The instruments for such a strategy are GHG taxes, emission trading,

stricter emission standards for classical air pollutant, etc.

Static frameworks and trends:

- There is uncertainty about the market conditions for CHP, especially considering the liberalization of the energy markets. Even though liberalization at first led to a decline in energy prices and therefore was an unfavorable development for alternative technology, in the future liberalization may be favorable for decentralized electricity generation because transmission and distribution costs could be saved.
- Among the various CHP technologies, advantages for fuel cells are ascribed due to the lower heating requirements in buildings as insulation has been improved and the increasing share of demand for electricity compared to the demand for heat. By this it is expected that the demand for heat is growing slower than the demand for electricity.
- The relationship between electricity and gas price is important: the smaller the ratio is, the less favorable it is for fuel cells. If the difference of prices for each kWh of gas is high, there are stronger incentives for a production of electricity.

4 Comparison of Fuel Cell Policies

4.1 USA

In the USA the research dealing with fuel cells is mainly financed by NASA, EPA, DoE and DoD on a federal level. With the funding, energy, environmental, industrial and military issues and objectives are pursued. Accordingly, a number of different state agencies are involved in the support of the development and application of fuel cells.

The NASA first developed fuel cells for the application in space travel in the 1960s. At present it is mainly involved in the development of smaller PEFCs that are also being used in space travel.

The program of the Department of Energy (DoE) is co-financed by the research and development activities of industry. The share of industry of the R&D expenditures is 40%. The support for PAFC was finalized, the funding was shifted in 2002 in favor of MCFC and SOFC technologies. Targets of the support are cost reduction regarding the materials used as well as enlarging the production capacities in order to utilize scale effects (Department of Defense 1998, p. 7). A program for R&D support for stationary installations with high temperature cells was budgeted at about USD 50 Mio./a in the mid-1990s. The aim of the program is to support the market launch of such units, not least owing to industrial-political reasons. A competitive industry is supposed to be created with these grants, using export chances as well. For the market launch support, the DoE has also, amongst other things, worked out national and international market analyses. The focus of the program was on participating in financing the construction of the demonstration installations.

The Environmental Protection Agency (EPA) is supporting a SOFC demonstration installation together with the DoE. This unit has a performance capability of 1.3 MW and it is being constructed at an EPA laboratory. The construction of the installation was planned for 1998-99 (Department of Defense 1998, p. 8).

The Department of Defense (DoD) has started, a total of three programs for the promotion of fuel cells: (1) the DoD demonstration program which financed the supply of PAFC units for military installations, (2) the DoD Climate Change Fuel Cell Program out of which other installations receive their subsidies and (3) the Navy Environmental Quality Program out of which a 250 kW PEFC unit for a naval base amounting to USD 1.75 million was financed.

Research in the US was initially concentrated primarily on the development of PAFC units until their market introduction. Currently, the focus is shifted on MCFC and SOFC units (Brown and Jones 1999, p. 8). In the year 1999 a public-private partnership for the further development of SOFC fuel cells was set up by the Department of Energy. The aim was to reduce the costs for this type from currently USD 4000/kW to USD 400 within 10 years. This is supposed to be realized with the help of a 3-10 kW block that can be flexibly combined with different units and produced in larger numbers whereby further potential cost-cutting measures can be reached. This program is designed to help the industry out of a Catch-22 situation: the price for fuel cells is currently too high to allow to sell larger numbers and, at the same time, the number of sold units is too small to allow viable cost reductions. Another objective of the program the realization of an efficiency factor of 40-60%; when combined with steam turbines it should go far beyond this mark. The alliance, named Solid State Energy Conservation Alliance (SECA), includes industry, research and government agencies. The program has been set up to run 10 years and the turnover is expected to be USD 500 million, of which USD 271 million are contributed from the public sector.

Apart from the financial grants, there are special regulations for patents on innovations developed within the program framework. These patents must be made available to the other industrial corporations taking part in the program for at least one year at “reasonable” licensing conditions and have to be offered non-exclusively. Thereby, the cooperative development of a single cell type is supposed to be made possible (Department of Energy 2002, p. 20).

In coordination with the Department of Energy and within the framework of the DoD Fuel Cell Demonstration Program, the Department of Defense has installed a total of 30 of the ONSI PC-25 as demonstration units. Furthermore, in the fiscal year (FY) 1993 USD 18 million and in the FY 1994 USD 18.75 million were made available. The aim of the program was to stimulate growth in the fuel cell industry and to examine the role of technology for the long-term energy strategy of the DoD (Brown and Jones 1999, p. 27).

Through an investment support program (Climate Change Fuel Cell Program, FY 95-97), the price of the ONSI installations was subsidized from USD 3000/kW to USD 2000/kW. Preferential treatment was given to those units that were installed in the US military sector. About USD 18 million were spent for this program (Brown and Jones 1999, p. 7; Department of Defense 1998, p. 11).

4.2 Japan

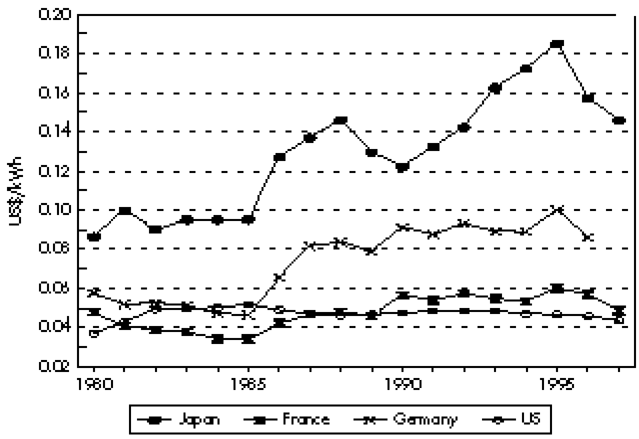
The development of fuel cells in Japan mainly took place within the frame of publicly financed programs that were undertaken by NEDO (New Energy and Industrial Technology Development Organization). Since 1993 their activities dealing with fuel cells are merged in the "New Sunshine Program". The program is continuing on the support measures initiated in 1974. NEDO started with the PAFC development support in 1981 and with the MCFC technology in 1984. Research programs on SOFC were initiated in 1989 and on PEFC from 1992 onwards (Homma 2001).

The so called "Moonlight Project" started in 1981, was supposed to run for 17 years and had a cash volume of USD 520 million. This as well as other energy and environmental projects were amalgamated into the New Sunshine Project in 1993. In the year 2002 the R&D budget for fuel cells was nearly doubled from USD 119 million to USD 220 million; for 2003 USD 288 million are foreseen (Department of Energy 2003).

As for the framework conditions regarding energy prices, it is worth mentioning that the Japanese electricity prices are the highest of all OECD states.

The high costs result from the comparatively high capital expenditure for power stations (higher costs for land, safety standards, compensation for the affected communities and an oligopolistic structure of the power station providers), higher fuel costs that are caused by environmental requirements and transport costs, demanding safety standards for power stations, an unfavorable relationship of the base and peak load, and finally, due to the refinancing of the subsidies supporting the use of local coal (International Energy Agency 1999).

Figure 5: Industry Electricity Prices 1980-1997

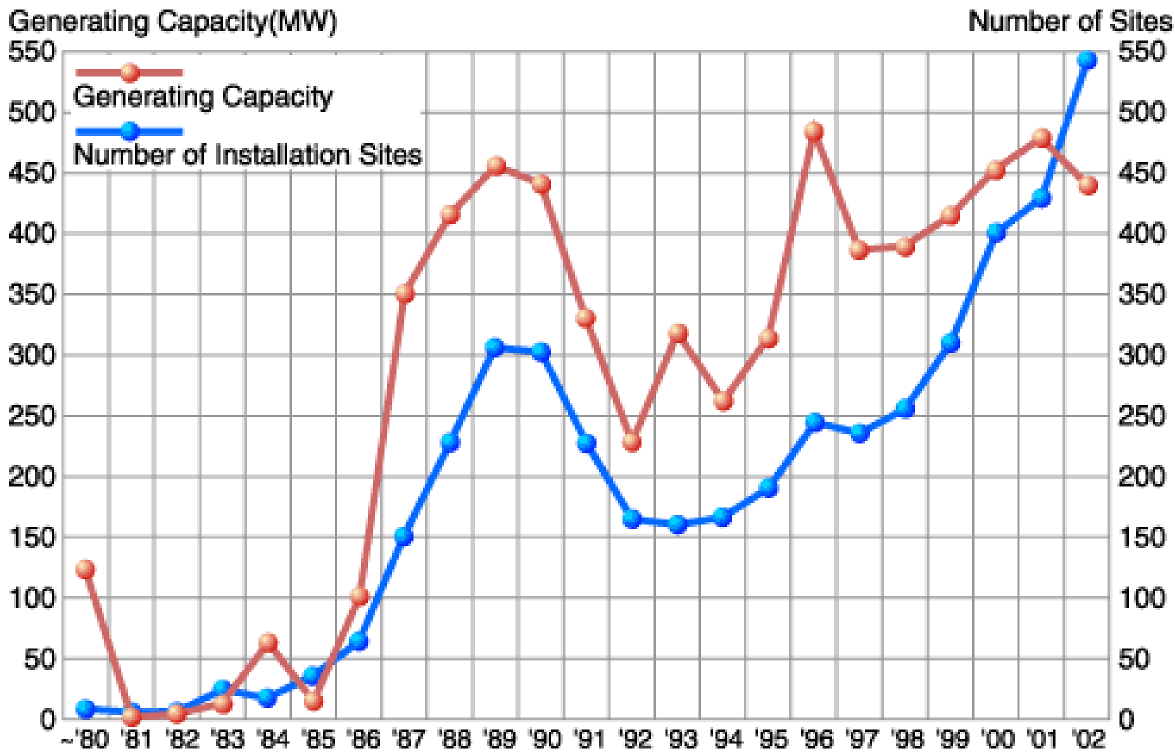


(International Energy Agency 1999)

The step-by-step liberalization of the energy markets, begun in 1995, in connection with the market appearance of independent power producers, will only have an effect on some of these factors. Therefore, in spite of the price decline that has been taking place since the mid-1990s, prices will not reach the same level as in other OECD countries.

The market for combined heat and power production in Japan has had a favorable development since the mid-1990s; therefore the necessary regulatory framework and infrastructure for fuel cells are available. However, generating capacity is far below that of Germany and the USA.

Figure 6: Number and Capacity of CHP Installations in Japan 1980-2002



Source: Japan Cogeneration Center http://www.cgc-japan.com/english/eng05.html

In Japan, the Tokyo Electric Power Company set up the world's largest PAFC unit, with a capacity of 11 MW (Brown and Jones 1999, p. 7). A 1 MW MCFC unit was in operation from 1999 to 2000. Since 2000, the construction of a 300 kW installation is being supported and for 2004 the operation of a 750 kW installation is planned. The grant budget for R&D in this technology segment was USD 17 million in 2002. About the same sum is envisaged for SOFC and PEFC development. PEFCs are supposed to be developed for both mobile as well as stationary applications. Altogether USD 156 million have been made available for a 10 year program; this amounts to four times the amount granted up to now (Department of Energy 2003).

4.3 Germany

Industrial research activities in Germany date back to the 1950s, when companies such as Varta or Siemens searched for possible applications for alkaline fuel cells. In 1982 a 100kW installation was build for a military submarine. Daimler–Benz demonstrated the automobile application for the first time in 1985 (Geiger 2003). Germany is the leading country regarding both the development as well as the installation of demonstration plants. About 75% of all applications in Europe are located in Germany (Geiger 2003).

Investing in fuel cells has, besides the support for renewable energy, become an important focus of the energy policy of the federal government led by a coalition of Social Democrats and the Green party. As part of a national sustainability strategy a pilot project "Virtual power station" of the German Energy Agency is planned. Hereby fuel cells in homes are connected with each other so that they achieve the effect of a power station (http://www.bundesregierung.de/Themen-A-Z/Nachhaltige--Entwicklung-,9064/Pilotprojekt-Energie.htm). The research grants were also much improved (see below). The amount of the grants therefore takes third place after the USA and Japan (Department of Energy 2003, Industry Canada, PriceWaterhouse-Cooper et al. 2003).

In mid-2000, all in all 16 fuel cell projects were realized in Germany, 14 of these with the above described PAFC ONSI units. The other two units are a PEM in Berlin and a MCFC in Bielefeld. Three of the older installations were shut down in mid-2000. Furthermore, 4 PEM units for small homes with 3 kWel were in operation (ASUE 2000: p. 16).

Power production from fuel cells has been given privileges by the CHP law that came into effect on 1.4.2002. The aim of the law is, among other things, to support the market launch of fuel cells. For fuel cell units that are set up after the law came into force in 2002, the network operators have to pay a supplement above the agreed-to supply tariff for a timespan of 10 years from the start of operation, amounting to 5.11 ct per kWh. This surcharge applies to new, small CHP installations. For older and bigger installations, lower surcharges are envisaged that are also degressive in character.

In addition, CHP installations are generally given preferential treatment by the law dealing with the introduction of the ecological tax reform. Since the stage 5 has come into force on the 1.1.2003, the law excludes energy self-production by units up to a capacity of 2 MW from the energy tax. Furthermore, CHP operators of installations with a yearly usage level of at least 60% are exempt from the ecological mineral-oil tax (0.366 ct/kWh for natural gas). At a yearly usage level of at least 70%, the exemption also covers the regular mineral-oil tax (0.184 ct/kWh for natural gas)

The Federal Ministry of Education and Research chose hydrogen technology and fuel cells as one of its main focus in its research activities. In this area, about EUR 110 million in research funds were spent between 1980 and 1996. In comparison, the public funding for the development of fuel cells in the USA was USD 73 million a year and in Japan USD 65 million (the figures are for 1995).

One interest of the federal government was the construction of a pilot and demonstration unit, realized by Solar Hydrogen Bavaria (Solar Wasserstoff Bayern, SWB), together with the state of Bavaria and partners in industry. Here a closed solar hydrogen system was supposed to be constructed, including the use of fuel cells. The focus of the grant activities, however, was in the area of fuel cells. Between 1990 and 1996 DM 79 million was spent, mainly for the development of SOFC, MCFC and PEFC fuel cells. In respect to the SOFC technology, the expectation has been expressed, that domestic lignite can also be used for power generation (BMBF 1996).

In the framework of non-nuclear energy research that was supported in the years 2001-2003 by the Federal Ministry of Economics and Labour with € 41 million/year, fuel cells were one of the main research areas (BMWi 2001, p. 31). There is the hope that with this technology, a leading role can be taken in the world markets for climate protection technology and an advantage can be achieved in the sector of installation construction (BMWi 2001, p. 56f.). The aim of the research grants is to create a competitive industrial sector (BMWi 2001, p. 9).

Recently, the ministries of research and education, economy and the environment set up a new joint research programme (“Zukunfts Investitions Programm, ZIP”) that aims to give support for the utilization of renewable energy technologies. Between 2001 and 2003 EUR 65 million were granted for projects related to hydrogen and fuel cells (Geiger 2003).

In Germany, high temperature cells are favored for stationary applications. The development of these has been supported by the Federal Ministry of Economics and Labour since the start of the 1990s. The support was concentrated on the development of CHPs with an output of 0.2-1 MW (BMWi 2001, p. 46).

Wengel et al. (2000) discuss as to how far Germany can be seen as playing a leading role in the international development and introduction of fuel cells. As supportive aspects for the stationary employment of fuel cells, they list:

- Experience with support measures with broad effect (feeding-in/supply remuneration),
- Willingness of consumers to invest for the environment and to invest in private owned real estate,
- A good manufacturing infrastructure and well as educated craftsmen,
- A trend towards a favorable power-heat mix,
- Redevelopment needs in decentralized heating units.

Impediments are:

- liberalized market with power station overcapacity and big suppliers (restrictive in the short term, maybe positive for FCs in the long term),
- dense, stable and relatively cheap electricity network.

Advantageous for the setting up of a lead market could be the high level of demand for off grid supply of electricity as here a higher willingness to pay exists. Fuel cells could be first used in off-grid areas or those that need a high level of reliability vis-à-vis the operation (hospitals, computer centers).

From these niche areas, cost-cutting measures can be realized using the experience gained as well as the scaling effects. Further markets can then be exploited. Supportive policies that use these niches can not be recognized at this stage in Germany in contrast to the USA.

4.4 European Union

Since the mid-1970s, fuel cell R&D is being supported (Department of Energy 2003). The European Union was participating in 135 research projects between 1989 and 1999; these had a project volume of ECU 381 million, of which EUR 92 million were financed by the European Union (Bahbout 2000). Between 1995 and 1998, about € 80 million was spent (Lievonen, Císcar et al. 2000, p. 68). In the year 2001, the budget was EUR 60 million (Department of Energy 2003). With the sixth research framework program, a further extension of the research activities is to be expected. In contrast to earlier research programs, targets for fuel cells as well as for the use of hydrogen as an energy carrier are explicitly named in the main objectives. For the period from 2003 to 2006, € 50 million a year are earmarked for the support of hydrogen and fuel cells (in comparison to $256 million in Japan and about $300 million in the USA for fuel cells alone) (http://www.forum-brennstoff-zelle.de/index.php?main=info&news=akt&akt=252).

The foci of the grants given up to now were support for a 250 kW PEFC unit in Germany, a 500 kW MCFC unit in the Netherlands and the development of SOFC stacks. In conjunction with the USA, a SOFC/micro-turbine installation with a capacity of 1 MW is supposed to be supported (Department of Energy 2003).

4.5 Canada

The research grants in Canada in the last 10 years have been mainly focusing on the development of PEFCs. CDN $ 179 million were spent between 1982 and 2002 for R&D grants (Industry Canada, PriceWaterhouseCooper et al. 2003). The company Ballard Power Systems, located there, is the leader in this sector and, since 1997, joined an alliance with DaimlerChrysler and Ford Motors that has invested USD 500-600 million in the development of fuel cells. In 2002, DaimlerChrysler announced further investments totaling USD 1 billion over the next 4 years (Department of Energy 2003).

A recent joint publication by several government agencies and companies wherein strategies for the commercialization of fuel cells are developed, recommends focusing on supporting demonstration projects as well as the early stages of market launches. This could be supported by public acquisition programs, supporting research networks that include scientists and developers, and encouraging training and the technical infrastructure. Canada should, furthermore, take on a leading role when it comes to the international standardization of fuel cells (Industry Canada, PriceWaterhouseCooper et al. 2003).

4.6 Other Countries and International Activities

Fuel cells have been supported in South Korea since 1985. In the period from 1992 to 2000, USD 20.9 million were spent for this. In Australia, the development of SOFCs has been promoted since 1992; including a USD 15 million grant for the development of a 100 kW unit (Department of Energy 2003).

In Italy, the development of fuel cells is being pursued by the company Ansaldo. It has concentrated on MCFC cells and has developed a 500 kW unit. Among the European countries Italy is second regarding the installed capacity, although far behind Germany (Cropper 2003).

The International Energy Agency (IEA) has, in the framework of the “Implementation Agreements” in which 15 countries are taking part, set itself the target of encouraging the international cooperation in the development and introduction of fuel cells. As part of this program, standards to test fuel cells were developed, networks of experts and international research cooperation were stimulated and market analyses were undertaken. This cooperation is supposed to be continued until the year 2003

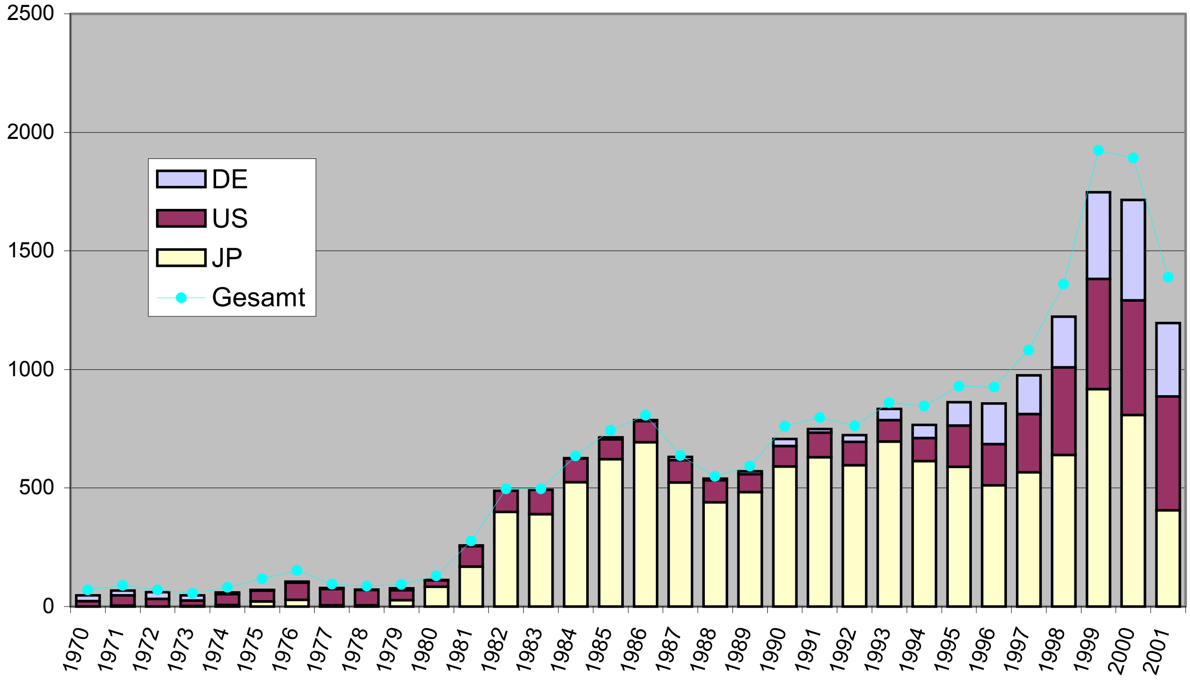
(International Energy Agency 1998; International Energy Agency 2000).

In 2002 a proposal for a World Bank support for installation in developing countries was issued. According to this programme up to 2000 USD per kW would be paid. In a first stage three demonstration projects should be selected, up to 2005 a total of 5-7 MW of fuel cells were expected to be funded (Cropper 2003).

4.7 Comparison of the Research Activities

Japan, the USA and Germany are the most important countries worldwide with respect to research activities. As an indicator of the relative position of these countries, patent activities can be utilized. For an analysis, the patent databank INPADOC (International Patent Documentation) was searched for the key-word fuel cell (and the corresponding German, French, Italian and Spanish terms), the year of registration and the country of origin (priority country). Most of the patent activities take place in the three countries already mentioned. This corresponds with the data from the Delphi 98 study that is briefly described below, where the questioned experts saw the highest R&D levels as being in those three countries (FhG-ISI 1998).

Figure 7: Patent Registration for Japan (JP), the USA (US) and Germany (DE)

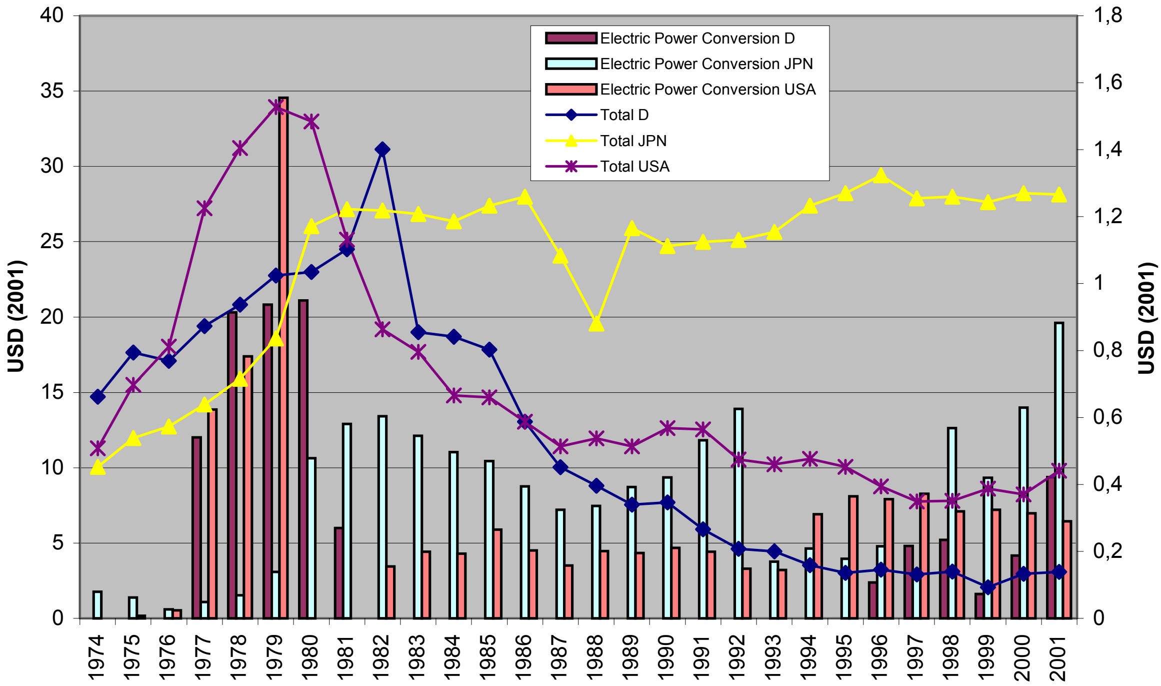


Datenquelle: International Patent Documentation (INPADOC)

What is noticeable is that Japan started off quite early (at the beginning of the 1980s) with a large number of patent registrations that have remained at a high level since that time. In the USA, there has been a large rise in the number of patents since the mid-1990s; with a short time lapse Germany has also reached this very high level. The drop for the year 2001 might be explained with a time lag in updating the databank.

The patent registrations in these three countries show a strong correlation to the public expenditure for energy research. In the following illustration, the per capita public R&D expenditures for general energy research in Japan, the USA and Germany are listed, as well as the per capita funding for "Electric Power Conversion" which includes inter alia the support for fuel cells.

Figure 8: Public Expenditure for R&D Energy Technology per capita



Source: IEA Energy Technology R&D Statistics;
Government Energy Technology R&D Budgets
http://data.iea.org/wds53/wds/eng/main.html

In Germany and the USA, relatively big sums were provided for in the area of electric power conversion up to about 1980. These were greatly reduced afterwards. In Germany, the research funding was even completely stopped in 1995. In comparison, in Japan substantial funds were put to use since about 1980. The USA and Germany have reached a comparable level only since the mid-1990s.

Barett (2002), in his patent analysis for the years 1999-2001, finds that 47% of the patents given out went to US organizations, 21% to German organizations and a further 16% to Japanese organizations. As another leading country, Canada is identified with 6% of the handed out patents. These results confirm that the USA, Japan and Germany are the leading countries in the research on fuel cell technologies; the US however has the highest share of patents. This may be explained with the choice of evaluated patent databanks. Barett, in his analysis, relates only to US patents and those of the World Intellectual Property Organisation (WIPO). The databank INPADOC being used here, however, contains data of altogether 71 organizations that give out patents.

Despite the considerable efforts in R&D of fuel cells, that can be read off the patent statistics, the introduction to a large scale market is according to a Delphi study of 1998 not close at hand. For the item *Solid Electrolyte Fuel Cells with a Performance Level of several 10 MW can be applied for* *regional CHPs as well as for decentralized electricity stations,* the experts for chemistry and materials expect it as a mean in the year 2017, the experts for energy & natural resources, on the other hand, only in 2020. The expectations for CHP installations in homes are even further apart. Whereas the experts for energy & natural resources expect a broad distribution in the year 2020, the experts for construction & living already expect the practical use of fuel cells for the decentralized energy supply of homes in 2007. *Combined high temperature fuel cell gas and steam turbine power stations with efficiency factors of around 70% are on the market* is expected as a median for the year 2015 (FhG-ISI 1998).

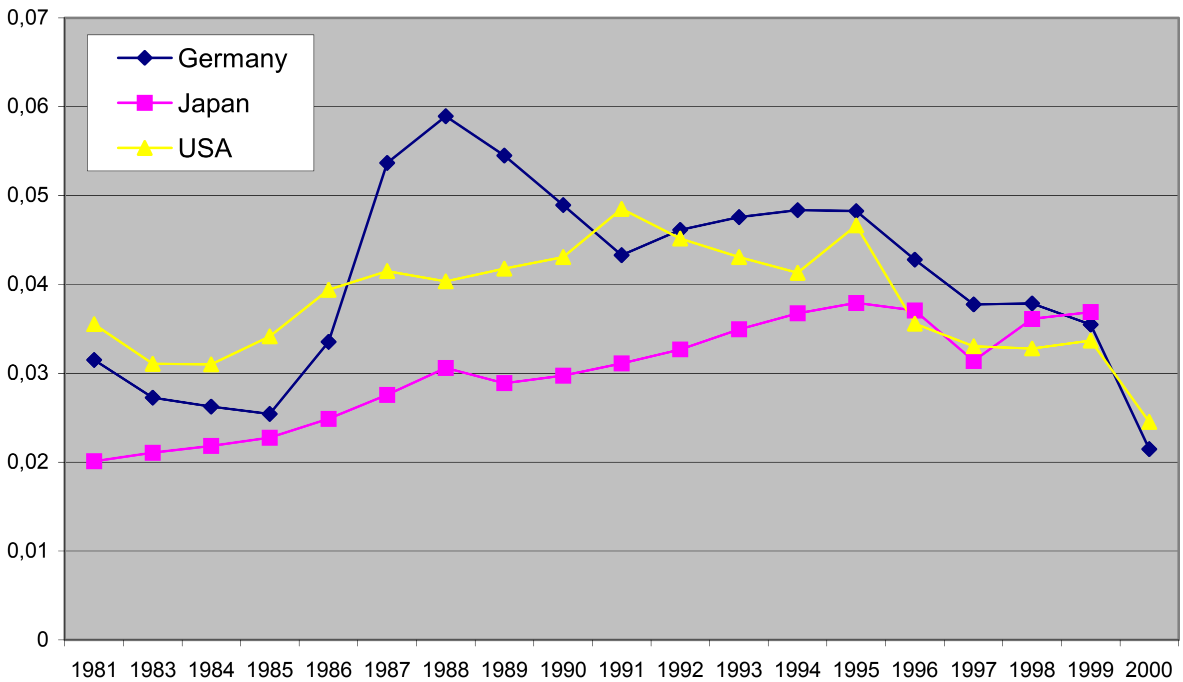
Stolten and Höhlein (2000) expect the market launch of fuel cells in 3-8 years, whereby first units for home energy supply, then busses, cars and, in the end, CHP installations are expected. The authors expect a very slow market penetration that could take 10-20 years and will not totally replace conventional technology.

4.8 Comparison of Energy Prices

The conditions for the use of fuel cells are better where electricity prices are high and gas prices are comparatively low. In the following graphics, the ratio of electricity and to gas prices in Japan, the USA and Germany are illustrated. In both illustrations, electricity prices are those for industrial use. Electricity prices for households are less relevant for CHP plants that are studied here.

The falling electricity prices in all three countries lead to a worsening ratio of electricity to gas prices.

Figure 9: Relationship Industrial Electricity Price/Industrial Gas Price

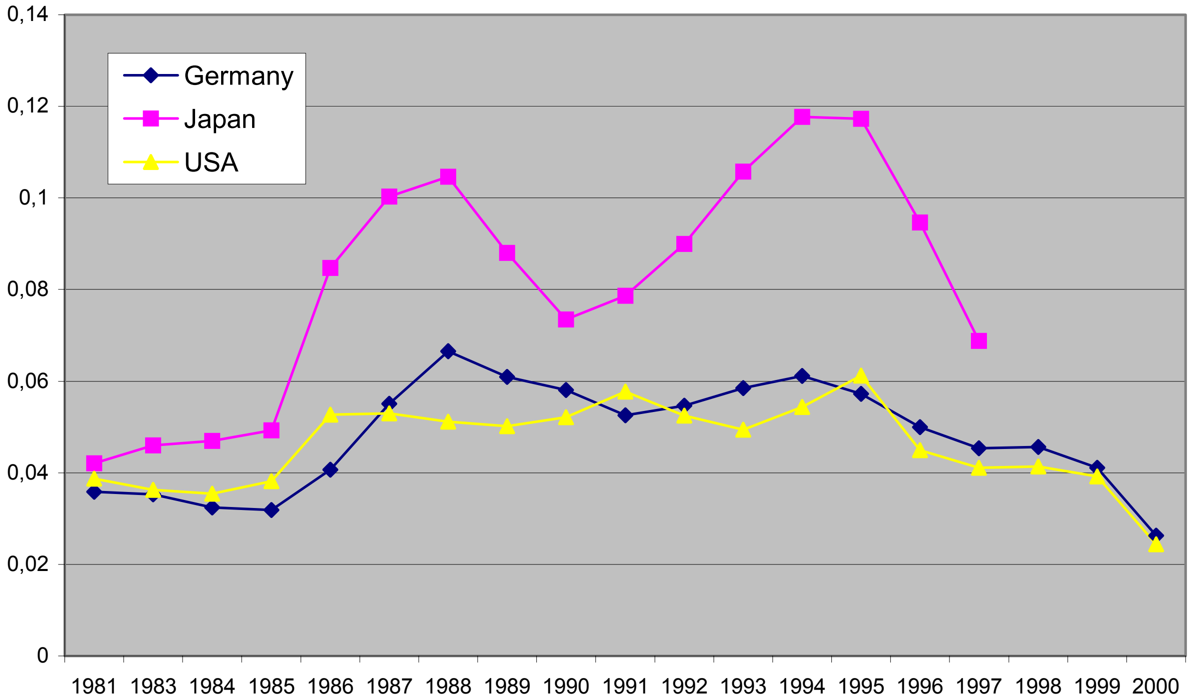


However, the picture changes when gas prices are operationalized in a different way. In the above graphic, the price for natural gas in industry is used, whereas in the graphic below the price is based on gas used to produce electricity.

Depending on which gas price is used, country ranking changes substantially. Even though Japan shows higher prices in this market segment than Germany and the USA, the much higher electricity prices there lead to a much more favorable ratio for the purchase by industry.

Even if one can assume the cheaper gas prices for energy generation with the industrial CHP using fuel cells, then the ratio between electricity and gas prices is the most favorable in Japan for the use of fuel cells. Germany and the USA are at about the same level.

Figure 10:Prices for Industrial Electricity/Gas for Energy Generation



5 Summarized Assessment

On the background of the pressing climate change and the efforts undertaken in many different countries as well as on the international level to reduce the emissions of CO_2, fuel cells might appear as a technology that provides a substantial contribution in this respect. Therefore, a worldwide market can be expected for this technology. It has, however to compete not only with conventional energy technologies, but also with CHP technologies as well as those for the utilization of renewable energy. Up to now, the costs for fuel cells are not competitive. The analysis of the development and support activities in the most advanced countries reveals that there are still considerable efforts required until a large scale market introduction is possible. Up to now the applications are limited to niches or demonstration projects that require large subventions.

It is not yet decided which of the innovation designs will be successful among the fuel cells and in competition with other technologies. There are advantages for high temperature fuel cells regarding the requirements on the fuel purity, the usable heat and the cost cutting potentials. However, PEM fuel cells are expected to be utilized for mobile applications, therefore learning and scale effects may be achieved earlier. It is hardly possible to locate regional differences in the stage of development of the different types among the countries. The USA are clearly ahead regarding PAFC fuel cells. Other development activities are carried out by companies that are active in several countries. E.g. Siemens-Westinghouse has roots in the US as well as in Europe, Daimler-Chrysler is active in North America as well as in Europe through its subsidiary MTU. In general, however, Europe and particularly Germany is less behind of the USA and Japan in respect of high temperature fuel cells.

There are considerable differences regarding the support for fuel cells in the countries under consideration. A comparison of the political measures undertaken and the framework that were identified to be important for the introduction of fuel cells is listed in the following table. The coding reads like 1 is the most favorable situation compared to the other countries, and 3 the least favorable. If two countries have almost the same value, no 2 was given, that otherwise indicate a medium position.

Table 2: Political measures in support of fuel cells

	USA	Germany	Japan
CHP support	2	1	3
R&D support	1	3	1
Long-term perspective	2	3	1
Coherence/ Integration	1	3	1
Safeguarding of market entry	2	1	3
Internalisation of external costs	3	2	1

The USA, Japan and Germany could be identified as the lead countries with respect to research activities and the installation of the first demonstration units. The research activities depend heavily upon public funding. Market forces alone are still not sufficient in order to mobilize private capital for the development of fuel cells. Because of the considerable increase in R&D funding in the USA, in Japan, Germany and the EU in the last few years it can be expected that the advantage of the three countries will continue to grow in the future. Within this group of countries, though, Germany has the lowest R&D budget at its disposal even if one takes the EU funds into consideration. Therefore the advantage of the USA, where currently the most important production locations of fuel cell stacks can be found, can be further increased. The more favorable framework conditions, the higher R&D funding may explain that with regard to number and performance level of the installed demonstration units, the USA and Japan, are ahead of Germany as well.

It is worth to mention the high level of cooperation taking place between the different government agencies in the USA. The programs to date are advertised, tendered and administered by several departments. In Japan, the sponsorship is concentrated within the Ministry for Industry. In comparison, the supporting activities in Germany and the EU seem to be largely uncoordinated.

When it comes to the safeguarding of the market introduction of fuel cells, Germany can be ranked on the first place, due to its feed in tariffs in favor of fuel cells. Since fuel cells are still in the stage of development, this instrument has no effects, yet. At best, it gives a long term signal for potential investors in the fuel cell development. The USA have had programs to subsidize the market introduction of fuel cells. By this grants it was possible to take over the leading role in the PAFC technology. Furthermore, its recent initiative on the promotion of SOFC primarily aims at preparing the market introduction of this type. Japan seems to concentrate on R&D programs rather than on market introduction.

The competitiveness of fuel cells is better compared to conventional technologies if the external costs of energy production are internalized. The degree of internalization can be indicated by the energy costs and – related to this – the strictness of environmental policy. In this respect Japan has to be placed first, Germany second, while the USA is lagging the international trend in environmental and particularly in climate protection policies.

Table 3: Framework conditions for fuel cells

	USA	Germany	Japan
Development Gas Price	1	2	3
Development Electricity Price	3	2	1
Relationship Gas/Electricity Price	3	3	1
Significance of Decentralized Energy Supply	1	3	3
Relationship Electricity/ Heat Use	2	1	3

The effects of liberalization of energy markets vary among the studied countries. Generally, there is a decline in prices both for gas as well as for electricity. While low prices for the fuel are favorable for the introduction of fuel cells, declining prices for electricity are an impediment. The ranking regarding the respective prices is shown in the table above. Beyond the differences in prices, the ratio between the prices for gas and electricity is of importance. The higher the difference is, the higher is the added value.

As for all CHP technologies fuel cells depend on the demand for decentralized energy supply as well as on the relationship between the demand for electricity and for heat. A higher demand for heat is advantageous for CHP technologies.

The conditions for the introduction of fuel cells depend directly on the general framework for CHP energy production. The ambitious European and German objective of doubling the share of CHP-generated electricity could lead to the market conditions for fuel cells being improved. However, this objective is not a binding commitment and up to now there is no directive issued. Furthermore, fuel cell technology is in competition with conventional CHP installations in this respect.

The costs of the existing units, already marketed in small numbers, can not yet compete with conventional technology. In order to achieve learning and scaling effects, considerable public (co-)financing of the market introduction is necessary. The USA and Japan go to comparatively great lengths in subsidizing the costs for demonstration installations. In Germany, besides the investment subsidies, feed-in tariffs for energy produced using fuel cells have been introduced recently. These are, however, not high enough to compensate for the higher investment costs of the fuel cell power generation. Mainly in the USA, demonstration installations in off-grid areas are being promoted. For these applications, higher costs are seen as being acceptable. With regard to public procurement in the USA, it is mainly the military sector that has come up with substantial funds. A corresponding use and implementation of niche applications in order to achieve learning and scaling effects isn't being undertaken in Germany with the exceptions of fuel cells that are used for submarines.

Expert questionnaires state that a market launch and gaining a substantial market share by the stationary fuel cells will only take place in 10-20 years. The securing of market success and the gaining of an advantage in international competition will depend on the experience and scaling effects gained by a step-by-step enlargement of niche applications during this time. The reduction of the current cost advantages by tightening environmental regulations for conventional power stations as well as lifting fuel prices would also be advantageous. In this respect, the strict Japanese standards are advantageous for the introduction of fuel cells. The strict environmental standards partly contribute to the high electricity price, therefore a more favorable electricity credit can be expected for fuel cells.

References

ASUE (2000). "Stationäre Brennstoffzellen. Grundlagen, Einsatzmöglichkeiten, Stand der Technik, Perspektiven." Kaiserslautern

Bahbout, A., G.P. Tartaglia and U. Bünger (2000). *Hydrogen Activities in the European Union Work-Programme.* 21th World Gas Conference, June 6-9, 2000, Nice.

Barrett, S. (2002). "Fuel cells R&D and intellectual property." *Fuel Cells Bulletin*(August 2002): 10-12.

Beise, M. (1999). *Lead Markets and the International Allocation of R&D.* 5. ASEAT Conference "Demand, Markets, Users and Innovation: Sociological and Economic Approaches", Manchester.

Beise, M. (2001). *Lead Markets. Country-Specific Success Factors of the Global Diffusion of Innovations*. Heidelberg/ New York, Physica.

Beise, M., J. Blazejczak, et al. (2003). "The Emergence of Lead Markets for Environmental Innovations."FFU Berlin FFU rep 03-02

BINE (2000). "Kraft-Wärme-Kopplung mit Bennstoffzellen. Projektinfo 5/00." http://bine.fiz-karlsruhe.de/pdf/publikation/bi0500.pdf

Birnbaum, U., H. Dienhart, et al. (1999). *Die Marktsituation von Brennstoffzellen*. Jahrestagung Forschungsverbund Sonnenenergie - Zukunftstechnologie Brennstoffzelle. 15.-16.9.1999.

BMBF (1996). "BMBF-Förderschwerpunkt Wasserstofftechnologie und Brennstoffzelle." www.hydrogen.org/Politik/bmbf.html last access: 7.8.2002

BMWi (2001). "Nachhaltige Energiepolitik für eine zukunftsfähige Energieversorgung. Energiebericht." http://www.bmwi.de/textonly/Homepage/download/energie/Energiebericht9MB.pdf

BMWi (2001). "Projekte mit Perspektiven. Energieforschung." http://www.bmwi.de/textonly/Homepage/download/energie/Energieforschung1.pdf

Brown, D. R. and R. Jones (1999). "An Overview of Stationary Fuel Cell Technology. Research Report prepared for the U.S. Army Forces Command."Pacific Northwest National Laboratory

Bünger, U. (2000). *Einsatzbedingungen und Marktchancen von Brennstoffzellen als Klein-BHKW.* Effiziente und umweltfreundliche Strom- und Wärmeerzeugung mit Brennstoffzellen. 20.-21. Juli 2000, Friedrichshafen.

Cirkel, H.-J. (2000). *SOFC Fuel Cells for Stationary Power Generation*. Hyforum 2000 - The International Hydrogen Energy Forum, 11-15 September 2000, Munich.

Cropper, M. (2002). "Fuel Cell Market Survey: Stationary Applications." http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_467_MarketSurveyStationaryApplications.pdf

Cropper, M. (2003). "Fuel Cell Market Survey - Large Stationary Applications."Fuel Cell Today http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_667_LgeStatSurvey0903.pdf

Cropper, M., S. Geiger, et al. (2003). "Fuel Cell Systems: A survey of worldwide activity."Fuel Cell Today http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_696_WorldWideSurvey1103.pdf

Department of Defense (1998). "Report to the Congressional Defense Comittees on the Utilization and Demonstration of Fuel Cells. August 1998."

Department of Energy (2002). "SECA Program Plan. Making Fuel Cells Available to America."National Energy Technology Laboratory and Pacific Northwest Laboratory.

Department of Energy (2003). "Fuel Cell Report to Congress."Department of Energy http://www.eere.energy.gov/hydrogenandfuelcells/pdfs/fc_report_congress_feb2003.pdf

Dienhart, H., J. Nitsch, et al. (1998). "Oekologische und oekonomische Bewertung der PEFC-Brennstoffzelle am Beispiel der Nahwaermeversorgung." http://www.dlr.de/TT/system/projects/BZellen/pefcbhkw.pdf

Dienhart, H., M. Pehnt, et al. (2000). "Analyse von Einsatzmöglichkeiten und Rahmenbedingungen von Brennstoffzellen in industrieller Kraft-Wärme-Kopplung und zentraler Stromversorgung (Zusammenfassung)." http://www.dlr.de/TT/system/publications/BZanalyse

European Commission (2002). *2001 - Annual Energy Review January 2002.* Luxemburg.

FhG-ISI (1998). "DELPHI '98 Umfrage. Studie zur globalen Entwicklung von Wissenschaft und Technik. Zusammenfassung der Ergebnisse; Methoden- und Datenband."Fraunhofer-Institut für Systemtechnik und Innovationsforschung im Auftrag des Bundesministeriums für Bildung, Wissenschaft, Forschung und Technologie (BMBF). Karlsruhe http://www.isi.fhg.de/publ/downloads/isi98b07/

Fritsche, U. R. (1999). *Umweltaspekte von Brennstoffzellen.* Workshop Status der Entwicklung und Anwendung der Brennstoffzellentechnik. 11. November 1999, Bremen.

Geiger, S. (2003). "Brennstoffzellen in Deutschland - Marktanalyse relevanter Tätigkeiten."Fuel Cell Today http://www.fuelcelltoday.com/FuelCellToday/FCTFiles/FCTArticleFiles/Article_621_GermanySurvey0603de.pdf

Hirschenhofer, J. H., D. B. Stauffer, et al. (1998). "Fuel Cell Handbook 1998."Department of Energy

Homma, T. (2000). *Present Status of Fuel Cells RD&D in Japan.* U.S. Eco-Energy 2002, February 27-28, 2002., Tokyo.

Homma, T. (2001). *Oral Presentation*. Properties and Phase Equilibria for Product and Process Design, Kurashiki, Japan.

Industry Canada, PriceWaterhouseCooper, et al. (2003). "Canadian Fuel Cell. Commercialization Roadmap." http://strategis.ic.gc.ca/epic/internet/inmse-epe.nsf/vwapj/FuelCellsTRM_e.pdf/$FILE/FuelCellsTRM_e.pdf last access: 13.05.2003

International Energy Agency (1998). "Advanced Fuel Cell Program. Strategy for the Period 1999 to 2003."

International Energy Agency (1999). *Energy Policies of IEA Countries. Japan 1999 Review*. Paris.

International Energy Agency (2000). "Final Report of the IEA Advanced Fuel Cells Implementing Agreement (1996 - 1999)."

Jänicke, M., J. Blazejczak, et al. (2000). Environmental Policy and Innovation: an International Comparison of Policy Frameworks and Innovation Effects. *Innovation-oriented Environmental Regulation. Theoretical Approaches and Empirical Analysis.* J. Hemmelskamp, K. Rennings and F. Leone. Heidelberg, New York, Physica**:** 125-152.

Klemmer, P., U. Lehr, et al. (1999). *Umweltinnovationen. Anreize und Hemmnisse.* Berlin, Analytica.

Lievonen, J., J. C. Císcar, et al. (2000). "IPTS-ESTO Techno-Economic Analysis Report 1999-2000." ftp://ftp.jrc.es/pub/EURdoc/eur19626en.pdf

Masaaki, T., Z. Nobuyuki, et al. (2003). "Development of Molten Carbonate Fuel Cell." *IHI ENGINEERING REVIEW* **February 2003**.

Mol, A. P. J. and D. A. Sonnenfeld, Eds. (2000). *Ecological Modernization Around the World. Perspectives and Critical Debates*. London/Portland (Or.), Frank Cass.

Nitsch, J. and H. Dienhart (1998). "Wirtschaftlichkeit und Marktperspektiven der Energiewandlung mit Brennstoffzellen." http://www2.dlr.de/TT/system/projects/BZellen/wrtstkt.pdf

Oertel, D. and T. Fleischer (2000). "TA-Projekt "Brennstoffzellen-Technologie". Endbericht."Büro für Technikfolgen-Abschätzung beim Deutschen Bundestag TAB-Arbeitsbericht Nr. 67

Padró, C. E. G. and V. Putsche (1999). "Survey of the Economics of Hydrogen Technologies."National Renewable Energy Laboratory

Pehnt, M. and J. Nitsch (2000). *Einsatzfelder und Marktchancen von Brennstoffzellen in der industriellen und öffentlichen Kraft-Wärme-Kopplung.* Konferenz "Brennstoffzellen...effiziente Energietechnik der Zukunft", 21.-22. Juli 2000, Friedrichshafen.

Pehnt, M. and S. Ramesohl (2003). "Fuel cells for distributed power: Benefits, barriers and perspectives."IFEU and Wuppertal Institute Heidelberg and Wuppertal

Pokojski, M. (2000). The first demonstration of a 250 kW Polymer Electrolyte Membrane (PEM) Fuel Cell for stationary application. Hyforum 2000, 11-15 Sep. 2000., Munich.

Rennings, K. (2000). *Redefining Innovation - Eco-Innovation Research and the Contribution from Ecological Economics. Ecological Economics*: 319-332.

Rennings, K. and M. Beise (2003). *Lead Markets of Environmental Innovations - The Case of Fuel Cells for Mobile Applications*. Mannheim.

Siemens (2002). "Environmental Report 2002." http://www.siemens.com/Daten/siecom/HQ/CC/Internet/Siemens_Corporate/WORKAREA/cseditor/templatedata/Deutsch/file/binary/umweltbericht2002_en.pdf last access: 7.8.2002

Simader, G. and T. Heissenberger (1999). "Brennstoffzellen-Systeme - Energietechnik der Zukunft? Entwicklungsstand und Perspektiven der stationären Brennstoffzellen-Technologie." http://www.eva.wsr.ac.at/publ/pdf/fuelcell.pdf

Stimmig, U., M. Rzepka, et al. (2000). *Primärenergie für die Brennstoffzelle: Quellen, Umweltbelastung und Energieverbrauch*. Die Brennstoffzelle. Zukünftige Querschnitttechnologie für den Industriestandort Deutschland? Konferenz der Friedrich Ebert Stiftung 6.12.2000, Berlin.

Stolten, D. and B. Höhlein (2000). *Die Brennstoffzelle. Querschnittstechnologie für den Industriestandort Deutschland*. Konferenz Die Brennstoffzelle. Zukünftige Querschnitttechnologie für den Industriestandort Deutschland? 6.12.2000, Berlin.

Theenhaus, R. and K. Bonhoff (1999). *Brennstoffzellensysteme - Ein Überblick.* Forschungsverbund Sonnenenergie - Zukunftstechnologie Brennstoffzelle. Jahrestagung vom 15-16.9.1999.

Wengel, J., E. Schirrmeister, et al. (2000). *Industrielle Kernkompetenzen und Beschäftigung: Brauchen wir die Brennstoffzelle für die Wettbewerbsfähigkeit des Industriestandorts Deutschland?* Die Brennstoffzelle. Zukünftige Querschnitttechnologie für den Industriestandort Deutschland? Konferenz der Friedrich Ebert Stiftung 6.12.2000, Berlin.