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The market for utility-scale fuel cell plants

Yasuo Watanabe [a,*], Masaru Matsumoto [a], Kazuhiko Takasu [b]

[a] MCFC Research Association, Technical Department, 3-10-10 Minami-Ohtsuka, Toshima-ku, Tokyo 170, Japan
[b] NEDO, Energy Conversion and Storage Department, 3-1-1 Higashi-Ikebukuro, Toshima-ku, Tokyo 170, Japan

Abstract

This paper is devoted to a survey of the current technology and future market for utility-scale fuel cell plants. The phosphoric acid fuel cell (PAFC) is entering into the stage where it is practically available for use with natural gas. Large capacity plants such as 11, 5 and 1 MW have been installed and operated in Italy and Japan. Their efficiency ranges from 36 to 42%. The molten carbonate fuel cell (MCFC) is in the demonstrating stage, both the fuel cell and the balance-of-plant (BOP) for natural gas. Demonstration plants of 2 and 1 MW have been under construction in the USA and Japan. Their efficiency will range from 40 to 50%. The solid oxide fuel cell (SOFC) is in the experimental stage around 100 kW for co-generation. Its conceptual system design has been conducted for both centralized and dispersed power plant in a cooperation with Westinghouse and NEDO. A market survey is now considered on the basis that future fuel cells will run for around 40 000 h in a stable manner with competitive performance. The market for fuel cells will be roughly at 2000 MW in Japan by the year 2010. Half of them will be installed for electric companies on the utility scale. The market will be shared between PAFC and MCFC by 10 and 90%, respectively. Current technologies have not reached the stage to precisely forecast when fuel cells will be entering into the market on a utility scale. At the present time, it is worthwhile to consider how the technological and economic requirements will be definitely achieved. After achieving these requirements, fuel cells will be positively introduced and socially accepted as the best energy converting option to save energy and environmental impact. Further efforts will be devoted to meeting the market from the technological and economic aspects.

Keywords: Market strategy; Fuel cells; Phosphoric acid fuel cells; Molten carbonate fuel cells; Solid oxide fuel cells

1. Background

Fuel cells have long been recognized as having excellent features such as high efficiency energy conversion, low CO_2 emissions and potential applicability to both small- and large-scale plants. Therefore, fuel cells have been intensively developed all over the world for higher efficiency and lower environmental impact.

Being at the turning point of the 21st century, we would describe the last hundred years as a century centered on economic growth. We feel it is now our duty to solve the problems described here and consider our position at the dawning of a new century: 'Century of Environment'. We share common responsibilities to finding new ways of saving energy and precious resources of this Earth. In Fig. 1 is shown that better human life will depend on a better balance of economics, natural resources and the environment on planet Earth. Global warming is caused by human activity. The worse effective parameters for global warming are energy consumption and CO_2 emission. These features show that researchers and engineers in any energy-related industry should sincerely consider a long-term strategy for keeping the Earth's environment healthy for future generations.

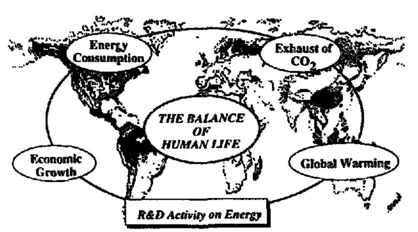

Fig. 1. Balance of human life.

2. Future power demand in Japan

We expect energy consumption to increase slowly, but steadily, at a rate of less than 1% per year. Fig. 2 shows the future perspective of the final energy consumption in Japan. Energy consumption is divided into three parts: (i) industry: (ii) residential and commercial, and (iii) transportation.

* Corresponding author.

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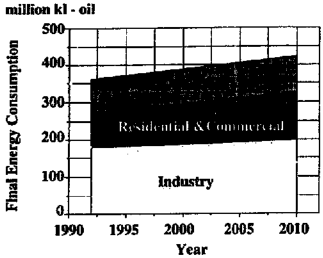

Fig. 2. Perspective of final energy consumption.

Higher increases will come, mostly, from residential and commercial areas whereas industry should continue at a more constant level pace. In fact, future economic growth in industry is not expected to rise as much in Japan. Residential and commercial demands and transportation are expected to increase steadily, as they are less effected by rising oil prices. This would indicate that we are unable to stop our pursuit of a more comfortable everyday life style, even if oil prices increase. Therefore, we must proceed with a wider range of R&D activities, if we are to save our planet.

2.1. Perspective of electric power supply

The electric power supply in Japan is forecasted to be increasing at a rate of more than 2% per year. Fig. 3 shows the perspective of the electric power supply in Japan. The overall energy consumption will increase at a rate of less than 1% each year. This would indicate that our modern way of life is indeed centered around electric power. Atomic power is expected to compensate future increased demand for electric power.

2.2. Lead time from plant planning to operation

By law, the delivering or supplying of energy should be based upon demand for today's needs in Japan, as well as for the increased demand of tomorrow. Fig. 4 shows the recent

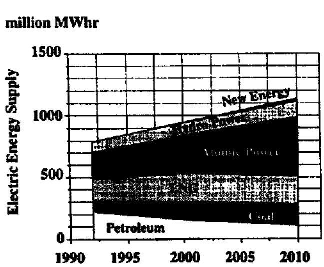

Fig. 3. Perspective of electric power supply.

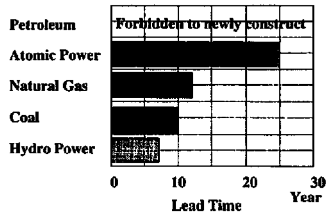

Fig. 4. Lead time from planning to running.

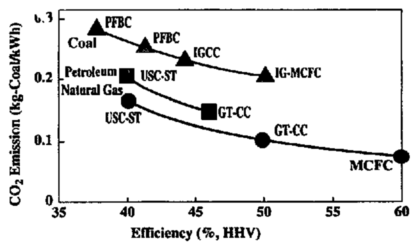

Fig. 5. CO_2 emission of MCFC and competitive technologies. PFBC: pressurized fluidized bed combustion; IGCC: integrated coal gasification combined cycle; IG-MCFC: integrated coal gasifacation MCFC; UST-ST: ultra super critical-steam turbine; GT-CC: gas turbine-combined cycle.

lead time from the first stages of planning of the actual plant operation in Japan. The lead time for atomic power is as long as 25 years though it is expected to compensate for increased demand. Therefore, the development of new energy technology is essential to improve efficiency in any energy-related company, as well as the electric power companies themselves.

2.3. Competitive technologies

Fig. 5 shows current and future power technologies for different fossil resources, pertaining to natural gas, petroleum and coal. Achievement of better efficiency will lead to the reduction of CO_2 emission from power stations. It indicates that fuel cells are the most promising technology not only for natural gas but also for coal. Fuel cells can reduce half or one third of the CO_2 emission from power stations.

3. National project for fuel cell plants

A Japanese national project for fuel cell plants has a 17-year schedule span, all of which started in 1981 as shown in Fig. 6. The market entry of fuel cells depends on sound technology and reasonable market price with the backing of government, sound technology being the most difficult aspect.

Research of PAFC in Japan was started to join the US Target Programme to be installed and be operated for com-

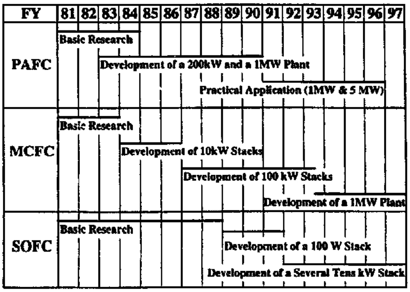

Fig. 6. Schedule of fuel cell R&D in NEDO.

mercialization. Japanese-made PAFCs open new channels for trade with demonstration plants in Amagasaki near Osaka and in central Tokyo with a 1 MW and a 5 MW plant in actual operation, respectively.

Research in MCFCs in Japan, on the other hand, was started independently from the USA. The MCFC Research Association is proud of recent accomplishments and is planning the construction of a 1 MW pilot plant in Kawagoe located near Nagoya in a near future. The MCFC Research Asscociation completed its basic research in 1984, developed its first 10 KW stack in 1986, followed by the success of a 100 kW stack, completed and approved by the Japanese government, November 1994. The construction of a 1 MW MCFC pilot plant has just been started.

The SOFC has succeeded in the goal to produce a 100 W stack cell, and are now working on several tens kW stacks. We can only report on the laboratory-scale small stacks.

4. Fuel cell power plants in the world

The PAFC is close to a commercial stage for co-generation systems, though it cannot be competitive with centralized plants, such as current LNG-combined cycle, because its efficiency is less than 42%. This means that its stack is operated at about 200 °C and its waste heat will be utilized for a supplemental energy source such as steam, hot water and chilled water for air-conditioning in urban areas.

The MCFC has sufficient potential to compete with central and dispersed power plants of more than several tens MW. It is expected to achieve a higher efficiency up to 60%, since its stack is operated at around 650 °C and its waste heat will be suitable for bottoming cycle with scale effect. This is also diversified not only for natural gas but also for gasified coal gas. On the other hand, it is under discussion whether it can be competitive with current co-generation systems.

The SOFC has the same potential for efficiency as the MCFC from higher operating temperature around 1000 °C. Therefore, its application is basically similar to and competitive with the MCFC.

4.1. PAFC power plants

Fuel for PAFC systems is steam-reformed natural gas or hydrogen. Coal-derived gas cannot be used since the catalyst of the cell stack is easily poisoned by a few ppm of carbon monoxide. The efficiency of this system is not as high as that of MCFC or SOFC. Therefore, heat as well as electricity should be used as the energy available on the site. The operation temperature being relatively low, or near 200 °C, water is a good coolant for the stack and a good heating fluid for air-conditioning.

In Japan, about 100 on-site PAFC plants have now been successfully operated for commercialization. Most of the PAFC plants have been operated at 50 to 200 kW power output under ambient pressure. Some of them have been operated for more than 30 000 h. Large-scale PAFC demonstration plants of more than 1 MW are now under operation in Japan as well as in Italy. They are being operated under pressurized conditions with the exception of a 1 MW on-site type at Tokyo Gas. An 11 MW PAFC power plant, at Tokyo Electric Power Company, is the largest fuel cell in the world. A 5 MW PAFC, at Kansai Electric Power Company, is a demonstration plant for an urban energy center. These four demonstration plants are the result of achievements from all over the world. Some of the cell stacks are from International Fuel Cell (IFC), made in the USA. Some of the reformers are from Halder–Topsoe, made in Denmark. All electric and gas companies in Japan have been contributing to the commercialization of PAFC.

4.1.1. Goi 11 MW PAFC power plant

An 11 MW PAFC co-generation plant was manufactured by Toshiba and IFC. This was constructed in 1993 at Goi Power Station, Tokyo Electric Power Company, without governmental support. It consists of 18 stacks, three lines with a series connection of six stacks each. This plant is still used mainly for research purposes of several MW power out-put.

4.1.2. Amagasaki 5 MW PAFC power plant

A 5 MW PAFC demonstration plant was designed for an urban energy center. This was just constructed at Amagasaki site, Kansai Electric Power Company. Half of this budget has been supported by the government, through NEDO. Stacks for generating 5 MW have been manufactured by the Fuji Electric Company. It consists of six stacks, two lines with a series connection of three stacks each. A reformer has been originally designed by Halder–Topsoe. They had a severe earthquake around Kobe last 17 January 1995. Fortunately, the facility was not damaged and has been successfully restarted for operation.

4.1.3. Tamachi 1 MW PAFC power plant

This power plant has been designed for an on-site type 1 MW PAFC demonstration plant inside a building in the center of the city, operating under ambient pressure. The system has just begun operation at Tokyo Gas Company in

Tamachi, Tokyo. Half of its budget is supported by the government, through NEDO. Stacks for generating 1 MW were manufactured by Toshiba. A reformer was designed by Toshiba with high-performance sulfur removal. This is the largest ambient pressure-type plant in the world, today.

4.1.4. Aem 1 MW PAFC

A 1 MW PAFC demonstration plant is located in Aem, Italy. The system had been manufactured by Ansald and IFC.

4.2. MCFC power plants

MCFC systems are classified into two types of reforming; external and internal reforming. The MCFC Research Association is also developing an internal as well as an external reforming type. Several kinds of fuel are available: natural gas, coal gas and bio-fuels.

In an external reforming-type MCFC, the outlet temperature of the cathode is normally as high as 650 °C. In this case, the cathode gas is recycled to cool the exothermic anode reaction. In order to generate power it is essential to recycle CO_2 from the anode to the cathode. Thermal gas energy from the cathode can be utilized for supplemental power generation. Especially in a large-scale plant, power recovery by turbine should be more suitable than steam recovery.

In an internal reforming-type MCFC, the reforming catalyst is built into the cell stack without a reformer unit, but instead an anode exhaust oxidizer. The advantages of an internal reforming type compared with the external type are: better fuel utilization, less cathode gas to recycle, and a smaller plant size. At this moment, we are afraid that the internal reforming type may be applied only for the application of natural gas in a large-scale centralized power plants, because coal-derived gas does not need any reforming.

All of the MCFC pilot plants with more than a 1 MW power out-put are not yet in operation. One is our 1 MW pilot plant of an external reforming type located in Kawagoe near Nagoya. The other is a 2 MW internal reforming type located in Santa Clara, California. Our external reforming MCFC will be operated under pressurized condition. On the other hand, Santa Clara's internal reforming type will be operated under ambient pressure. These two different concepts come from what we are pursuing for large-scale centralized power stations and the Santa Clara's demonstration of on-site-type co-generation.

4.2.1. Kawagoe 1 MW MCFC pilot plant

We have just started the construction of a 1 MW MCFC Test Station at Chubu Electric Company's Kawagoe Power Station. The entire budget is sponsored by the government, through NEDO. All of the main BOP facilities have been newly developed for ten years into future large-scale power plants. The system consists of four stacks in total, two lines with a series connection of two stacks each. Each line is manufactured by Hitachi and IHI, respectively. The cell areas of both lines are the same, 1 m^2, similar to the PAFC cell area of Fuji and ONSI. This plant construction will be completed within two or three years.

4.2.2. 2 MW MCFC Santa Clara's demonstration plant

A part of the budget of the 2 MW Santa Clara's demonstration plant has been provided by the US government. The stacks of internal reforming type are manufactured by ERC. These stacks will be operated under ambient pressure. They consists of 16 stacks in total, two lines with a series connection of eight stacks each. This plant is near completion.

4.3. SOFC power plant

For the SOFC as for the MCFC, various fuels can be, in principle, be used: natural gas, coal gas and bio-fuels. The SOFC is the simplest system of all fuel cells but is still in laboratory scale because of its high operating temperature, e.g. the solid electrolyte makes thermal stress between ambient temperature and 1000 °C, causing difficulties in assembling the stacks. Westinghouse and NEDO are working on a conceptional design of a 300 MW plant.

5. Competitive technologies: LNG-combined cycle

In recent years we have made maximum efforts to improve the efficiency in power stations. The efficiency of power generation is around 49% with the current technology, as shown in Fig. 7. In a smaller scale, the competitive technologies for fuel cells are the diesel engine and the gas turbine. On a large scale, there is a gas turbine combined cycle and a steam turbine. In the face of many unsolved problems we must overcome a 49% efficiency with the current levels of technology, available today.

A combined cycle is our strongest competitive technology for a large-scale power plant. Its efficiency has recently improved to 49% because its operation temperature reaches up to 1350 °C under normal conditions. The MCFC still has the advantage of a 40–60% efficiency. The MCFC takes advantage for exhaust pollutants of NO_x and CO_2 over a combined cycle. The present investment cost of the MCFC is ten times more than that of a combined cycle. The MCFC

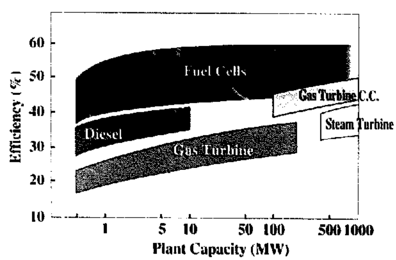

Fig. 7. Fuel cells and competitive technologies.

is at the stage of completion of its pilot plant. However, a combined cycle has been in the power market since the last twenty years.

6. Perspective on future cost

From an economic viewpoint, many surveys show the future target prices to be competitive with those of current power technologies. From this viewpoint, the future cost of an MCFC plant is evaluated to be 14 cent/kWh at the construction cost of $ 2800/kW in Japan.

From the manufacturing viewpoint, on the other hand, few surveys show perspective on future cost. First, because the technology of cell stacks have not been on a commercial level but on a development level. Second, it is under discussion how well fuel cells will be potentially performed. Third, it is still not obvious when the manufacturing level will enter into mass-production stage and how many users there will be.

Judging from the present 1 MW MCFC plant construction, 'cell stacks' are the most important factor to determine the overall cost. Roughly speaking, the fuel cell stack cost will be shared in a 1:3 or 1:4 ratio of the overall construction cost. The cost of the MCFC will be expected to go down after the cell stacks will become well performed and mass produced. This includes that large-scale plant cost shall be reduced by scale merit of BOP such as reformers and gas turbines.

The perspective gap between economic and manufacturing viewpoint will be diminished after increasing technical completeness in manufacturing cell stack with better cell performance on the basis of the definite prospects.

7. MCFC R&D strategy for market entry

7.1. Stack performance

We should not hesitate to say that our present stack performance is insufficient for commercialization. Fig. 8 illustrates the developent of our MCFC stack.

In general, the characteristics between current density and voltage give such a linear relationship that voltage decreases

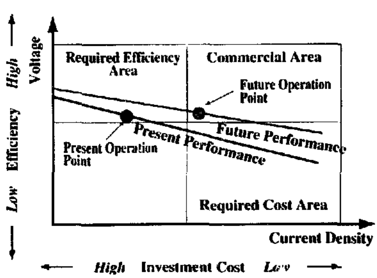

Fig. 8. MCFC development for commercialization.

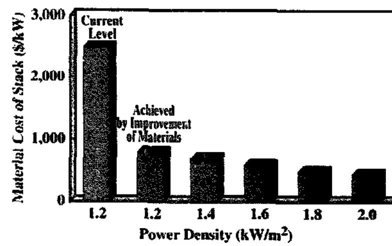

Fig. 9. Power density and material cost.

as the load current increases. The operating voltage is nearly proportional to the efficiency. The current density corresponds also to the plant construction cost, e.g. increasing the current density reduces investment cost.

Today, we are operating the present stack with a better efficiency without any reasonable investment cost. Once we compromise to a lower investment area, efficiency should decrease. Therefore, we will develop a new stack with a better performance for commercialization, operated with a good efficiency at a reasonable investment cost, material science being the key technology.

7.2. Material cost

As for materials and their structural development, we will examine a more uniform temperature distribution with a more uniform gas distribution as well as a smaller number of stack parts and thinner material for each layer with less contact resistance between each part. It will contribute to achieving a higher power density as well as a lighter stack with less heat loss and a better efficiency of each BOP facility. It will lead to a larger capacity of MCFC systems. Fig. 9 shows the current and future power density versus stack cost for commercialization by improving of the structure of the system and use of materials.

7.3. Stack life time

From the viewpoint of cost evaluation as well as plant operation, it is an important factor how long the stacks will be working. Fig. 10 shows the relationship between stack life and power generating cost in a future large-scale MCFC system. It indicates that stack life time is very sensitive to generating cost during 40 000 h, e.g. about five years. Our 1 MW pilot plant is scheduled to operate for 5000 h. We have already started to develop better performance stacks with longer life.

7.4. Mass production

Our study shows in Fig. 11 that are many possibilities to reduce the stack cost with mass production, for which we will construct automation factories. The first stage is semi-auto-

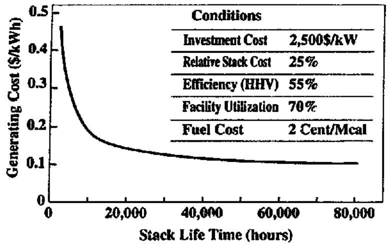

Fig. 10. Relationship between stack life and unit cost.

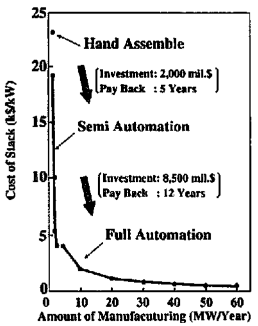

Fig. 11. Cost evaluation of stack manufacturing.

mation, the second stage full-automation. The MCFC power generation system should be competitive with the combined cycle, after these accomplishments of mass production have been achieved.

7.5. R&D strategy for market entry

Our R&D strategy for a market entry to the power generating business is focused on the construction of 1 MW MCFC pilot plant and the transfer our research to an R&D for a better performance and longer life stacks. Then we will enter the market with semi-automation stack factories, and after confirming the better stack performance in terms of market entry, we will start its commercial stage.

7.6. Future plant examples in the market

7.6.1. A few tens MW dispersed-type MCFC power plant in an urban area

A few tens MW dispersed-type MCFC power plant will be located in an urban area and may be co-generated with both electricity and steam. Gas fuel can be supplied from natural gas-line networks. Fuel utilization should be more than 70% with a smaller emission of NO_x and CO_2.

7.6.2. Natural gas fueled several hundreds MW MCFC power plant

A future several hundreds MW natural gas-fueled MCFC power generation plant will be located on a seashore with 700 to 800 stacks as well as 30 to 40 reformers.

7.6.3. Coal-gas fueled 1000 MW class MCFC power plant

A future 1000 MW class coal-gas fueled MCFC power generation plant as our final target, will be located on a seashore far away from a big city. Our research has just started on tolerance levels of MCFC in case of coal-gas impurities. We should overcome many issues to accomplish a coal-fueled MCFC power station.

8. Electricity utility industry law

Japanese electric power companies are regionally divided into nine districts. Transmission lines in each company have been connected. An surplus demand in a specific region for a specific time is controlled to be successfully supplied through connection lines between regional power companies. Previously, the law forbade any newcomers to enter into the power business because of strict governmental regulations.

Amendment of this law, now, enables newcomers to enter the power business with little government permission. First, the existing power companies can make contracts to purchase generated power at reasonable costs from the newcomers into the large-scale power generation business. Second, the newcomer in small-scale power generation business can generate and transmit the electric power to newconsumers in specified areas like urban energy centers, independently from the existing power companies. The market for fuel cells will expand by the renewal of this law. Fuel cells are a promising technology for entry to the market by supplying electric power as well as heat and air-conditioning.

9. Fuel cell market entry in Japan

Fuel cells have excellent features such as high efficiency energy conversion, low emission of CO_2 and are potentially applicable to both small- and large-scale plants. At this moment, many fuel cells are looked upon as to distribute power output to isolated locations.

A market survey is now considered on the basis that future fuel cells will plateau at around 40 000 h with a competitive performance. The fuel cell market will be segmented as shown in Table 1 with a total of roughly 2000 MW by the year 2010 in Japan. Half of them will be installed for electric companies on the utility scale. The market will be shared between PAFC and MCFC by 10 and 90%, respectively.

For commercialization, we must solve issues related to improvement of stack performance and establishment of reliability and cost reduction.

Table 1
Perspective of fuel cell market in Japan

Year	1995	2000	2010
Utility scale (MW)		40	1150
Non utility scale (MW)	30	160	1050
Total capacity (MW)	30	200	2200

10. Conclusions

We live with many benefits from both the Sun and the Earth everyday without hardly noticing. When visiting the forests or the mountains to appreciate nature, we sometimes find previous magnificent natural settings lost within the past decades. The spirit of fuel cells is indeed lofty and noble for saving natural resources. Roughly speaking, only a 1% improvement in efficiency will lead to a 4 to 5% reduction in CO_2 emissions. Japan has been struggling to effectively utilize energy to become one of the least CO_2 exhausting countries per capita. Such R&D activities will lead to an 'efficiency revolution'. After all, we do want to keep nature and the place we live as beautiful as possible, with the help of fuel cells.

We must overcome many problems facing fuel cell development for commercial use. In order to achieve this, we shall make it all worthwhile, to continue the endeavor for long time with effective research and development with a large amount of development costs through international information exchanges.

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