Journal of Power Sources, *29* (1990) 37 - 45

FUEL CELL APPLICATIONS AND MARKET OPPORTUNITIES

KAREN TRIMBLE and RICHARD WOODS
Gas Research Institute, 8600 West Bryn Mawr Avenue, Chicago, IL 60631 (U.S.A.)

Fuel cells represent an exciting generation technology for the next decade. Their efficiency, modularity, environmental characteristics and siting flexibility will permit their use in a variety of applications worldwide. Market opportunities for fuel cells will depend, to a large extent, on their individual operating characteristics. With phosphoric acid fuel cell technology positioned for commercial introduction in the early 1990s, the Gas Research Institute is currently focused on the development of advanced fuel cell technologies for expanded cogeneration applications in the commercial and light industrial market sector.

Several of the more important benefits of advanced fuel cell technology for cogeneration applications are high conversion efficiencies (>45% HHV for practical systems), high quality by-product heat, and the potential for direct natural gas utilization. The high efficiencies of advanced fuel cells are particularly attractive where thermal to electric ratios are low. In these applications, the higher electrical efficiencies permit fuel cell systems to be sized larger than competing cogeneration systems in a given application, hence, servicing a greater kilowatt load with gas. Additionally, the high exhaust temperatures enhance coupling with thermally driven chillers, again displacing electric peaking demand.

Table 1 identifies a number of potential markets for fuel cell generators. The residential, aerospace/military and transportation markets/applications are beyond the scope of this paper.

Figure 1 attempts to summarize the applications of the fuel cell types and their support within the National Fuel Cell Coordinating Group.

All told, there are about 3300 individual utilities in the first four categories in Table 1. An additional 2800 cogenerators/independent power

TABLE 1

Fuel cell market sectors

Electric utility power generation
Independent power production
Industrial cogeneration
On-site/commercial cogeneration
Aerospace/military
Residential cogeneration
Transportation

Elsevier Sequoia/Printed in The Netherlands

NATIONAL FUEL CELL COORDINATING GROUP	FUEL CELL TECHNOLOGY				
	AFC	SPFC	PAFC	MCFC	SOFC
Department of Energy (DOE)		Transportation	Electric Utility Cogeneration - Commercial Transportation	Electric Utility Cogeneration - Commercial - Industrial	Electric Utility Cogeneration - Commercial - Industrial
National Aeronautics and Space Administration (NASA)	Space Power	Space Power			
Department of Defense (DOD)	Military				Military
Electric Power Research Institute (EPRI)			Electric Utility IPP	Electric Utility Cogeneration IPP	Electric Utility Cogeneration IPP
Gas Research Institute (GRI)			Cogeneration - Commercial	Cogeneration - Commercial - Industrial	Cogeneration

Fig. 1. Application interest by fuel cell type for national funding organizations.

producers also supply electricity, though generally to a single customer (themselves). Though cogenerators/independent power producers still serve relatively few customers, they have been a most important category in terms of new capacity additions in recent years, accounting for 14 000 MW of the total capacity added since 1980.

The commercial and industrial sector in the United States represents a large potential market for fuel cells. The commercial sector includes four million sites representing approximately 175 000 MWe of cumulative peak demand. There are many applications in the commercial sector which have sufficient electric and thermal loads to make fuel cell cogeneration economically attractive. Table 2 presents a number of these applications and some general characteristics of each. This market is projected to grow by 2 - 4% per year with more than 50% of the market being comprised of office buildings, stores and appartments.

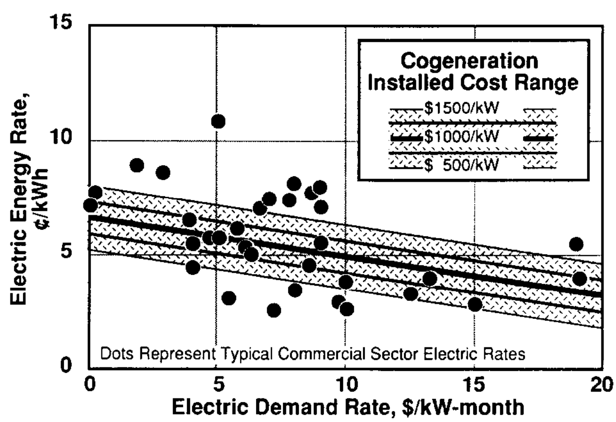
An economic screening of the potential commercial market reveals that only a portion is economically attractive or feasible. Based on inputs regarding local energy rates, operating modes, and sizing strategies, the economically feasible market size has been estimated. If the long range objective of a full catalog of grid-independent power plants at installed costs of $1000/kW is realized, an economically feasible market of 18 000 MW or about 10% of the commercial sector's population results. If 100% of this economically feasible market were captured, it would represent 0.52 trillion cubic feet (U.S.) of additional annual gas sales.

Many U.S. cities examined exhibit commercial retail energy prices that make gas-fueled cogeneration economically feasible for systems with

TABLE 2

Commercial applications

Application	No. sites	Average electrical use (kW)	Average thermal load (MMBtu)
Hospitals	7100	300 - 800	0.8 - 2.0
Hotels/motels	56470	100 - 850	0.3 - 3.0
Supermarkets	29550	240 - 300	0.2 - 0.3
Restaurants (18 - 24 h)	20500	60 - 90	0.4 - 0.6
Nursing homes	14950	60 - 70	0.4 - 0.6
Large office buildings	24000	200 - 800	1.1 - 3.5
Appartment complexes (>20 units)	54000	50 - 400	0.3 - 2.5
Shopping centres	7820	210 - 2200	0.4 - 3.5
Laundries	75000	20	0.6
Educational facilities	13000	500 - 2000	0.5 - 1.0



Base Line Assumptions:
30% Electric Efficiency; 75% Overall Efficiency; 80% Boiler Efficiency; 20% Annual Capital Charge Rate; 80% Capacity Factor; 50% Heat Utilization; 0.5 ¢/kWh O&M Rate; & $4.00/MMBtu Gas Price.

Fig. 2. Self-generation economics; commercial sector or on-site cogeneration.

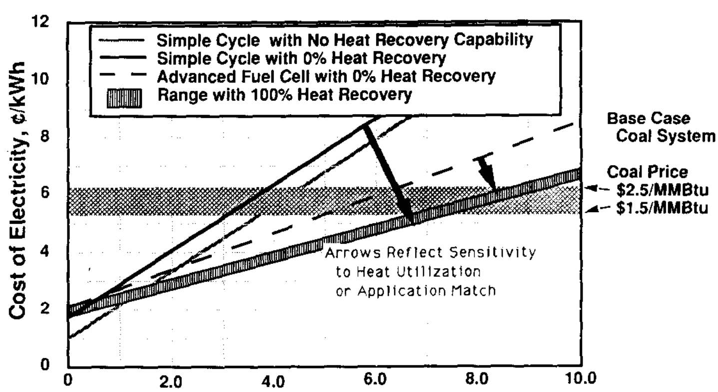
installed costs of approximately $1000/kW. Figure 2 illustrates the commercial viability of these systems at a number of typical cities. Efficiencies in the range of 30% (HHV) are typical of reciprocating engines and small turbines in this size range. Experience to date indicates that installed costs for these competing systems in the range of $1000 - 1500/kW are typical for small cogeneration systems in the 50 - 500 kW range. These costs reflect the high costs for engineering, site assembly, and installation.

GRI has projected that on-site fuel cells, under mature market conditions, will have an installed cost of approximately $1000/kW. This is based on economies of scale for a continuous production line operation supplying several hundreds of megawatts per year. During the production of the introductory units, the installed costs are projected to be relatively expensive ($2000 - 3000/kW).

To realize the immense potential that exists within this sector, technology and market developments are required to reduce first cost and increase system utilization efficiencies. Cost effective integration of absorption chillers is the key to effective utilization of by-product heat in many commercial applications and thus can enhance market penetration. Other uses of by-product heat include water heating, space heating and steam production. Fuel cell systems for commercial sector applications are expected to range from 25 to 1000 kW in size. Overall efficiencies approaching 80% have been projected for these systems.

The industrial market is approximately equal in size in terms of peak electrical demand to the commercial sector. This market segment includes about 300 000 sites with 20 000 of those accounting for over 90% of the energy use. Fifty percent of this market is represented by the chemicals and primary metals industries. The small industrial market (<2 MWe) represents about 10% of the industrial market or approximately 15 000 MWe peak demand — the food industry comprises about 20% of this market. Advanced fuel cells are expected to be used in municipal waste treatment plants, breweries, chemical plants, paper making, petroleum and metals refining and chlor-alkali production. PAFC technology is limited in this application due to the lower quality heat available and strong competition from conventional technologies.

The industrial sector is characterized as having relatively high thermal to electrical needs which minimize the economic advantages of high electric generation technologies. Figure 3 illustrates the impact of heat utilization



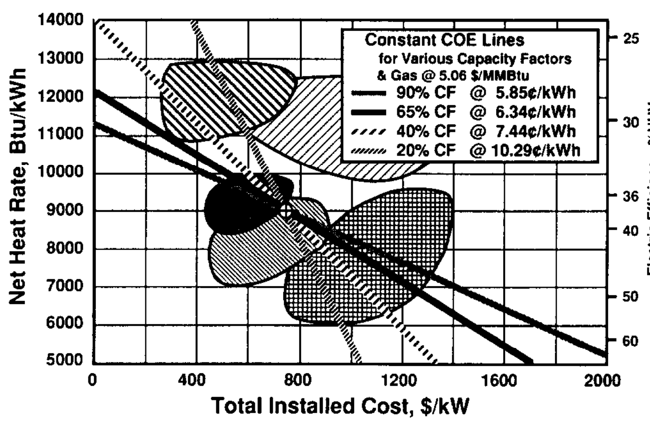
Baseline Assumptions: 65% Capacity Factor; 12% Annual Capital Charge Rate.
Simple Cycle: 11,400 Btu/kWh Heat Rate, Capital Cost $400/kW without HR & $700/kW with HR @ 75% Overall Efficiency
Advanced Fuel Cell: 6,300 Btu/kWh Heat Rate, Capital Cost $900/kW and 75% Overall Efficiency

Fig. 3. Impact of heat recovery; industrial cogeneration.

for both a simple cycle turbine and an advanced fuel cell. As can be seen, the advanced fuel cell is much less sensitive to heat utilization.

Characteristics other than efficiency and cleanliness which enhance industrial fuel cell use are: (1) a fuel cell power plant can provide d.c. power at lower cost than a.c. power, (2) it may be possible to utilize industrial process off-gases in the fuel cell rather than combust the gases as is usually done, and (3) the fuel cell process might be directly integrated into industrial processes, particularly in the chemical process industry.

Figure 4 shows constant cost of electricity lines for various capacity factors for a typical natural gas fired combined cycle power plant. Plants such as this can be considered the main competition for advanced fuel cell systems in a similar size range. In order to be economical at all operating philosophies, the fuel cell installed cost must be below $800/kW at a heat rate of 8000 Btu/kWh or less. If capital costs exceed this target, fuel cells will only be competitive in more traditional baseload operation.



Baseline Assumptions: 14 MW CC Power Plant, 65% Capacity Factor; 12% Annual Capital Charge Rate, $750/kW Capital Cost, 9000 Btu/kWh Heat Rate, 0.026 ¢/kWh Variable and 10 $/kW-yr Fixed O&M, and $5.06/MMBtu Gas Price

Fig. 4. Gas-fueled economics; 14 MW combined-cycle.

We can surmise, with reasonable certainty, that fuel cell market introduction will occur with on-site units which are fueled by natural gas. This is due to many factors. First, and most obviously, these units are smaller, representing a required step in the development of the later, coal-fired systems. Second, the systems are simpler, not requiring pressurization and not requiring significant development of other system components. The commercialization of gas-fired systems, therefore, should be of low relative risk and more rapid than the federally funded coal-based systems primarily supported by the U.S. DOE.

With demand for electricity growing by about 2 - 3% per year, a significant burden will be placed on the demand for raw energy sources (natural gas, coal, nuclear and hydropower). Given the long lead times currently associated with construction of new generating capacity, it appears that currently planned additions will not be sufficient to meet end-use electricity demand in the mid to late 1990s. These lead times, tightening environmental constraints and the inability to site nuclear plants may force utilities to consider incremental capacity additions, initially with gas-fired combined-cycle plants, and later with more efficient, fuel cells coupled with coal gasifiers. Both molten carbonate and solid oxide technologies project market penetration in the 1995 - 2000 period, precisely at the time the need for new capacity rapidly increases.

Independent power production also has the potential to be an important source of power. The May 1989 Study by The American Public Power Association (APPA) includes analyses of the deregulation underway in the industry and concludes that fuel cells are becoming increasingly attractive to public power because of these changes. The competition to fuel cells in public power is principally purchased power and diesel generators because combined cycle or coal plants are too large for most public utilities, and joint action agencies lack control of sufficient transmission capacity to take advantage of scale of large plants. Tightening emissions regulations have made it increasingly difficult to site diesel generators, hence fuel cells become an important alternative to purchasing power in an unregulated environment. In the near term, therefore, public power may be the only significant electric utility market in the U.S. A profile of public power is provided in Fig. 5.

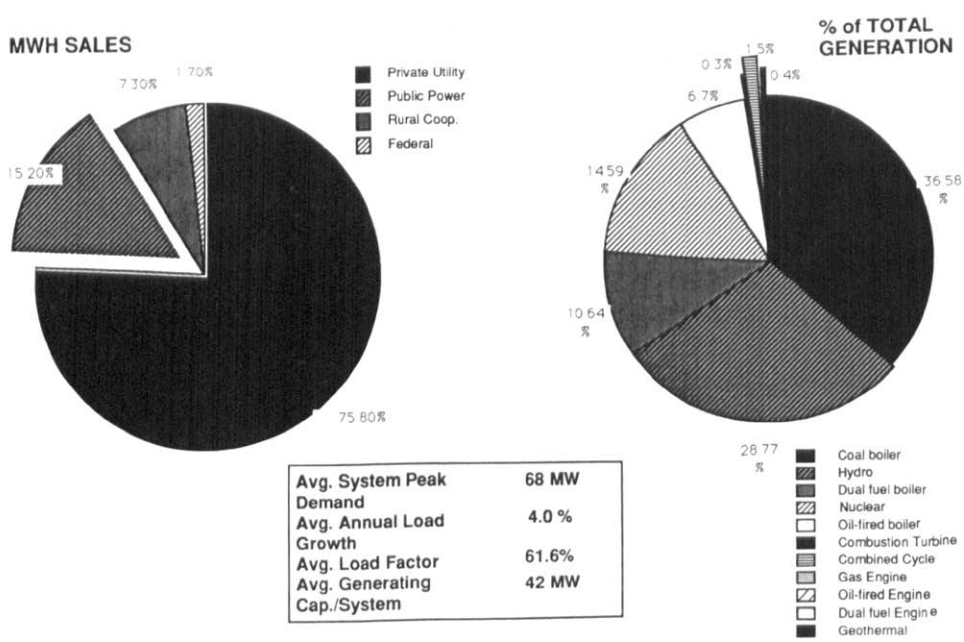


Fig. 5. Profile of public power.

Renegotiated power contracts plus load growth projections show a potential for 93 gigawatts over the 1996 - 2010 time frame. A 'likely early market' analysis was performed which results in a total of 14 GW over the time frame, or about 900 MW/year. Their study indicates that fuel cells can begin to enter this market at an allowable installed cost of $1500/kW. True competitive prices, however, are closer to $800/kW for PAFC or SOFC plants and $1000/kW for MCFC plants.

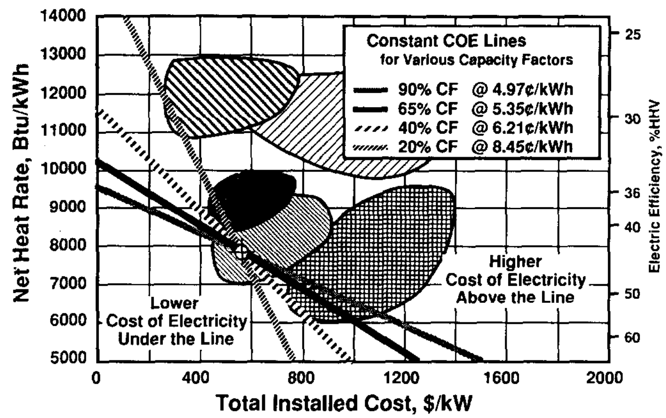
Independent power plants will be installed close to the load, increasing the probability for waste heat utilization. These plants will be approximately 50 MW or less in size. Dispersed generation has the potential for reducing capital costs and lead times required, and could reduce or postpone the need for new large-scale electric generating capacity. Advanced fuel cells, initially operating on natural gas, could fill this role. Initially the fuel cells will operate as load followers (1500 to 7000 h per year) but as the gap between coal and oil/gas prices widens, and as the need for baseload additions grows, fuel cell modules would be installed at central sites. Ganging several of these 20 - 50 MW generators and coupling them with a coal gasifier will complete the development and evolution of fuel cell power plants for gas and electric utility applications.

As discussed earlier, demand for electricity will outstrip supply leading to capacity shortfalls by the mid-1990s. Though present reserve margins are currently excessively high, planned capacity addition, when combined with retirements, will erode this reserve quickly. In 1995 the gap between total additions needed and total supply could be greater than 30 000 MW. By the year 2000, this figure could exceed 100 000 MW. Assuming that new units must be ordered five years in advance, the market for new units should take off in the mid to late 1990s.

An April 1987 study sponsored by EPRI indicates a 187 000 MW shortfall in electric capacity by the year 2010. In this study fuel cells were compared with competing technologies such as coal plants, combined-cycle plants and combustion turbines under a range of conditions for the capture of this market. For this comparison, fuel cells are estimated to cost $920/kW and have a heat rate of 7800 Btu/kWh. Under these base case assumptions, fuel cells capture 15 000 MW by the year 2010 or 8% of the market. With mature costs and heat rates meeting and/or exceeding this criteria, both carbonate and solid oxide fuel cell technologies project healthy futures if commercialization schedules can be adhered to.

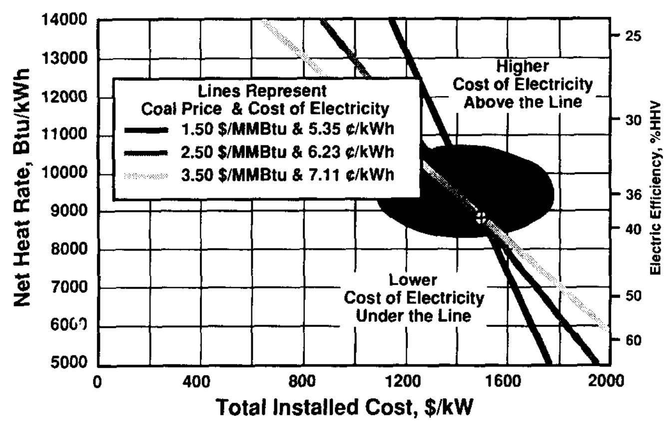
The long-range market for fuel cells in the electric utility sector is based on integration with coal gasifiers and bottoming cycles for base load central station application. If fuel cell cost and performance targets are met, these will be the coal-fired option of choice as they are the most efficient and most environmentally of any coal consuming generation technology.

Figures 6 and 7 show economics of large scale utility power plants for natural gas and coal, respectively. Figure 6 suggests that it becomes difficult for advanced fuel cell power plants integrated with a coal gasifier to compete with natural gas fueled combined-cycle plants in the multi-hundred MW size



Baseline Assumptions: 380MW CC Power Plant, 65% Capacity Factor; 12% Annual Capital Charge Rate, $570/kW Capital Cost, 7800 Btu/kWh Heat Rate, 0.026 ¢/kWh Variable and 10 $/kW-yr Fixed O&M, and $5.06/MMBtu Gas Price

Fig. 6. Gas-fueled economics; 380 MW combined-cycle.



Baseline Assumptions: 380MW IGCC Power Plant, 65% Capacity Factor; 12% Annual Capital Charge Rate, $1500/kW Capital Cost, 8800 Btu/kWh Heat Rate, 0.17 ¢/kWh Variable and 40 $/kW-yr Fixed O&M

Fig. 7. Economics of coal-fueled power plants.

range. Their costs are approximately equal to combined-cycle systems for intermediate and baseload operation. Either environmental aspects or technical risk can tip the decision-making scales either way in the future. Allowable installed costs increase however, as shown in Fig. 7 for integrated gasifier combined-cycle power plants, making coal fired fuel cell plants more attractive when compared with like fuels.

Conclusions

The commercialization of fuel cells appears imminent with the debut of International Fuel Cell's PC-25 in 1991 - 1992. A number of orders have been placed for this unit, with expanding interest in Japan and regionally in the United States. Due to environmental constraints, the California market appears to be poised to take off. The South Coast Air Quality Management District has reviewed this technology and will host one of the first PAFC units sited. They estimate the California market at approximately 1000 units per year. Once doors such as these are opened, a window of opportunity will exist for improved and/or higher temperature fuel cells to penetrate the market.

Internal assessments performed at GRI generally show favorable economics for fuel cell systems if installed costs can reach their target goals. These observations are summarized below:

- In the commercial sector, cogeneration is competitive with electric energy changes in many cities. In this market, fuel cells can provide a one to two cent advantage over reciprocating engine based systems, mainly due to their higher electrical efficiency.
- In larger sizes and using higher efficiency gas fired equipment, gas fueled cogeneration is competitive with coal fueled power generation up to a natural gas price of $6 - 7/MMBtu. Advanced fuel cells, due to their high electrical efficiency, are much less sensitive to heat utilization making them easier to site. The opportunity also exists to integrate these systems directly into the process, especially in the chemicals industry and to provide direct current electricity for industries such as metals refining.
- The advanced fuel cells compete well with gas and coal fired combined cycle equipment in the smaller size ranges. For example, a 22.5 MW molten carbonate system can produce electricity at approximately the same price as a 100 MW combined cycle plant. When comparing equal size plants, advanced fuel cell power plants are superior to both combined cycle and steam injected gas turbines for both baseload and intermediate duty. Supplemental firing of these systems can provide added thermal to electric flexibility.
- For large scale utility plants, fuel cell power plants have a competitive cost of electricity when compared to alternate coal fueled technologies. A cost *versus* heat rate trade-off analysis shows that a 1600 Btu/kW h heat rate improvement approximately balances a $100/kW increase in capital costs at a fixed coal price of $1.5/MMBtu.

Fuel cell systems are thus expected to enter the market following successful demonstrations of commercial scale technology. These systems must, however, provide evidence of economic competitiveness and efficiency advantages when compared to conventional forms of energy service (purchased electricity and gas) and/or energy conversion technologies (*i.e.* engines, turbines, combined-cycle, etc.). It is therefore crucial for manufacturers and sponsors alike to concentrate efforts toward the development of low cost production techniques. This factor, above all others, will likely decide the future acceptance of fuel cell technology in the 1990s and beyond.