Journal of Power Sources, 29 (1990) 119 - 130

THE FUTURE OF FUEL CELLS FOR POWER PRODUCTION

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The fuel cell, which William Robert Grove conceived of in 1839, has engendered high hopes over the last two decades. Conventional technologies have served power production needs well over the course of the 20th century, but those with vision have begun to anticipate a time when a new generation of technologies would emerge — technologies that are close to environmentally benign, with characteristics more of solid-state devices than of rotating machines, with high efficiency, in small packages. Some have linked technologies to be used after the year 2000 with a fuel that is also environmentally benign — hydrogen.

Developers of generating equipment see the opportunity to move the manufacturing and construction operations from the field to the factory, producing truck-transportable pallets of equipment. Electric utilities see a path to a reduced burden from the environmental impact of their smoke stacks and by-product wastes and from the growing network of transmission lines. Researchers see an opportunity to participate in the development of the first completely new technology for electric generation since nuclear power. And, environmental advocates see the opportunity to support a technology capable of having a major impact on global atmospheric and water problems. At least, it is hoped these interest groups have these visions.

In many respects it seems that fuel cells have been the elusive solution in search of a problem, or problems, yet to develop. Their environmental performance begs for a day when air and water quality constraints are so great that fuel cells are the only option one has for power production. Their fuel flexibility characteristics beg for a day when fuel availability and price considerations require a technology that can utilize low-Btu waste gases from landfills, and natural gas, and methanol with great efficiency and flexibility. These and other scenarios have kept public and private funding of fuel cells somewhat steady since the 1970s.

The capital and operating cost of the fuel cell as a power producer has received attention, but any disadvantageous comparison has been augmented with fuel cell 'credits' that are based upon one or more constraints on existing technologies.

This orientation has put fuel cell developers in the position of chasing constraints that continue to be 'in the future', not 'today' constraints. Air quality problems, in general, have only begun to suggest pervasive problems

0378-7753/90/$3.50

in building power plants. In the meantime, progress in developing fuel cells has still not reached the goals of cost and reliability necessary for entering the commercial market. The *potential* for the product and the *potential* market have yet to merge into a viable commercialization setting.

Long-term opportunity — is it still there?

In examining the future of fuel cells for power production, look first at the long-term need for power production capability and technologies. Are fuel cells still a promising option?

Environmental considerations

In the last decade, the U.S. electric utility industry has spent staggering amounts on pollution control: capital investments for SO_2 emissions control alone were more than $60 billion. The annual costs for air pollution control exceed $10 billion; for solid waste disposal, $1 billion. And these amounts, of course, do not include the additional hundreds of billions of dollars spent to improve nuclear plant safety or in the cancellation of planned nuclear capacity or for other environmental expenditures for non-generation operations.

The summer of 1988 with its unprecedented temperatures — reinforcing a pattern through the 1980s — again focused major attention on the environment. Concerns over global warming are reinforcing action to address other areas of environmental concern, including acid rain and ozone depletion.

With the call for increased attention to the environment by both national parties, environmental constraints facing the deployment of new electrical generation will only grow. These concerns will likely involve emphases on higher efficiencies, cleaner fuels and wise energy use.

Substitution of fuel cells for conventional power plants should improve air quality and reduce water consumption and waste water discharge. The generation of electricity now produces more particulates, sulfur oxides and nitrogen oxides than all other stationary sources combined. Fuel cell power plant emissions are ten times lower than those specified by the most stringent environmental regulations. Fuel cells also produce lower carbon dioxide (CO_2) emissions than conventional generation, a question of increasing concern due to the so-called 'greenhouse effect'.

Because the electrochemical reaction of the fuel cell produces water as a by-product, little if any external water is required for power plant operation. This low water use is in marked contrast to large steam electric power plants that require large quantities of water for cooling. Waste water discharges from fuel cell systems are also lower and the quality is superior compared with conventional fossil-fueled power plants, scarcely requiring any pretreatment prior to disposal in many communities. Fuel cells eliminate or reduce water quality problems associated with thermal discharges, power plant site runoff, and the disposal of wastes from air emission controls.

The quiet, electrochemical nature of fuel cells eliminates many of the sources of noise associated with conventional steam-powered systems, thus easily complying with OSHA (Occupational Health and Safety Administration) standards. No ash or large volume wastes are produced from fuel cell operation. Land requirements are acceptable, and connecting transmission corridors are not required as is the case with outside power sources. Because of their comparatively small size, absence of a combustion cycle, state-of-the-art safety systems, and low pollutant emissions, fuel cells are among the least hazardous methods of energy conversion.

Size considerations

Planning flexibility, including modularity, results in strategic and financial benefits to the utility and its customers. Because fuel cell power plants may be built within two years from the time of order, and because performance is largely independent of plant size, they can be used to increase utility system capacity by small increments in response to customer needs.

By better matching increases in electric demand, long periods of overcapacity are avoided, lowering average fixed costs over time. And, if demand growth is uncertain, the fuel cell's short lead time becomes even more valuable. A utility can slow or accelerate its response to growth. Also, as experience is gained with fuel cells, utilities may be able to reduce required reserve margins while maintaining the same reliability, resulting in lower fixed costs.

Efficiency considerations

The fuel cell can convert up to 80% of the energy from its supply fuel into useable electric power and heat. Current phosphoric acid fuel cell (PAFC) designs offer 41% electrical conversion efficiency on a high-heating value basis, with 46% electrical conversion efficiencies for PAFC possible in the near term through currently known science and engineering. The Electric Power Research Institute has estimated that advanced molten carbonate fuel cells (MCFC) may achieve electric efficiencies greater than 60%, exclusive of a bottoming cycle, which could raise efficiencies even higher. Such efficiencies are unprecedented. Furthermore, a fuel cell's efficiency is largely independent of its size. Fuel cells can operate at half their rated capacity while maintaining high fuel-use efficiencies.

Fuel cell power stations located close to loads can also reduce costly transmission lines and transmission losses. Possibly more important, fuel cells sited in municipal systems can minimize transmission line dependence in joint power supply arrangements.

Another important attribute of the fuel cell is its ability to cogenerate; that is, to produce hot water and lower-temperature steam at the same time as it generates electricity. Its ratio of electric to thermal output is approximately 1.0, while for a gas turbine the ratio is about 0.5. This advantage means that a fuel cell matched to a thermal load will have approximately twice the electric output of a combustion turbine matched to that same load*. In smaller sizes of interest to most public power systems, fuel cells are also more efficient (by about a factor of two) when compared to, for example, the 15 000 Btu/kW h heat rate of a 2 MW combustion turbine. The fuel cell's load following capability, while maintaining high efficiency, may also give it an advantage in cogeneration markets with varying heat demands.

Fuel considerations

Though initial fuel cell power plants may be designed to be fueled primarily with natural gas, the cells require hydrogen. The fuel processor that produces this hydrogen-rich gas allows the use of a variety of low-sulfur gaseous and liquid fuels including propane, methanol and ethanol. Advanced fuel cells should also be able to operate economically on these fuels as well as gasified coal.

Operational considerations

Fuel cells have beneficial operating characteristics matched by no other technology. These characteristics save costs in meeting system operating requirements. Dynamic operating benefits include load following, power factor correction, quick response to generating unit outages, and control of distribution line voltage and power quality control.

The solid state power conditioning system of the fuel cell power station can be used to control real and reactive power independently. Control of power factor and line voltage, to meet load can minimize transmission losses and reduce requirements for reserve capacity and auxiliary electrical equipment such as capacitors, tap-changing transformers and voltage regulators.

When new generating capacity is added to an electric power system, substation equipment sometimes has to be upgraded because of the expectation of increased fault current (which lowers the reliability of the electric system). However, with fuel cell power units, it is not necessary to upgrade the fault-current interrupting capability of existing substation equipment, because the short circuit generated will be limited.

Fuel cell units have an excellent part-load heat rate and can respond rapidly to transient loads. For example, the heat rate of a phosphoric acid demonstration unit is anticipated to be approximately 8300 Btu/kW h at rated power and to increase only slightly at 50% of rated capacity. Also, it is expected to be able to ramp from 30% of rated power to 100% of rated power in only 7 s. Spinning reserve requirements can thus be lessened when fuel cells are used.

Cost and design considerations

The fuel cell power plant, as a long-term option, must produce electricity at costs competitive with today's alternatives. Without this expecta-

*Dependent upon a user's thermal load requirements it may be economical to install boiler systems to supplement the cogenerated heat produced by fuel cell systems.

tion for a generally competitive technology, the manufacturers and the early buyers will not absorb the higher costs and risks of the market entry activities.

The cost target identified by several electric utilities considering 11 MW demonstrations in 1987, was approximately $1100/kW (1989 $). A recent market study [1] identified a similar figure for public power systems, for a long-term mature cost goal.

Phosphoric acid technology is expected to yield power plants that are only marginally competitive in a setting with low coal prices, and abundant gas and oil supplies, especially when new technology risk factors are considered. The installed cost of molten carbonate and solid oxide technologies is expected to be favorably competitive by a margin of 10% or greater.

The expectation that a technology can achieve competitive costs is important to establishing the basis for proceeding with commercialization. Site-specific applications that yield high 'credits' for the absence of certain constraints can provide high value opportunities for limited-production early-market units, but they are not useful for evaluating the mature market.

This expectation of a competitive technology is more easily realized if the basis for design is simple, with few integrated thermal loops, limited rotating machinery, and minimum maintenance due to water treatment, waste-product removal and catalyst regeneration.

In summary, the longer-term power production business is likely to require a technology with the characteristics of fuel cells. Power producers will require these characteristics in smaller-size packages suitable for modular capacity expansion, and small enough to serve individual community requirements. The technology and the power plant design must be simple enough that the early buyer can expect that cost reduction efforts will be successful. And, the power produced must have costs competitive with power produced from alternative means.

Fuel cells fit these long-term needs, expected to develop beyond the year 2000. Cost considerations lead one to favor the advanced fuel cell technologies, but phosphoric acid, with progress made toward simplicity of design and low stack costs, is also a contender.

Near-term opportunity — how do we reach the long term?

In the near term, the circumstances favorable for fuel cell commercialization require identification and development of the right technologies, aggressive manufacturers, and a market that needs the characteristics described above *today*. Even with this, the additional support of government policy (national and local) and research funding may be necessary. Without the combination of factors described above (technology, manufacturer, market), and barring severe environmental constraints, getting through the costly, risky early-market phase will be difficult.

In the U.S., one sector of the electric utility industry is trying hard to find the right technology/manufacturer combination to work with as the early market. Public power systems are looking for a commercial-scale demonstration and market entry program that leads directly to commercial products in the mid-1990s.

The American Public Power Association (APPA) initiative, described by their October 1988 Notice of Market Opportunity [2], identifies the interest of municipally-owned electric utilities. These potential fuel cell buyers need the characteristics of fuel cells, today, in relatively small packages. Their systems are generally smaller in size, serving urban loads, with siting, environmental and transmission constraints. Some municipal systems have difficulty today siting any conventional technology within their service territory.

Profile of public systems

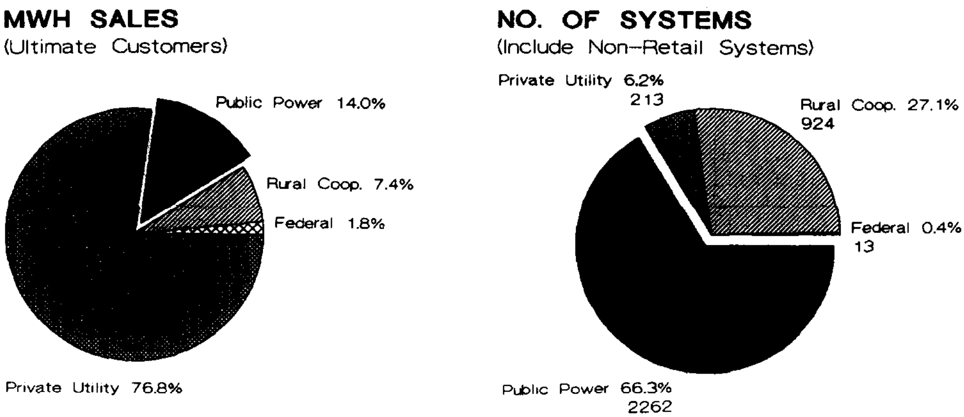
Public power represents 14% of the U.S. electric utility industry measured in kilowatt hour sales to ultimate customers, and 12.5% of the industry in terms of installed generating capacity. The public power sector is made up of approximately 2000 individual municipal systems, 60 joint action agencies which supply groups of member systems, and other wholesale suppliers (see Scheme 1).

Some salient characteristics of this market are:

- Public power is growing at a faster rate than the industry as a whole (4% *versus* 2.1% growth in kW h sales to ultimate customers)
- Public power retail rates are often lower than surrounding private and rural cooperative utilities (an average of 35% lower than the industry as a whole)
- 83% of the public power energy sales to ultimate customers is supplied from purchased power contracts
- The largest 20 municipal systems represent about 37% of the retail energy (kW h) sales of public power systems
- Three-quarters of the systems are above 10 MW in size, and about 150 systems have peak loads in excess of 100 MW
- Public power has 89 000 MW of installed capacity today
- Approximately 18% of the energy purchased by public power systems is supplied by joint action agencies; about 900 systems are members of joint action agencies

Public power structure

The public power segment of the U.S. electric utility industry is made up of individual systems that sell power within the approximate boundaries of cities, small and large, and so-called public utility districts (located principally in Nebraska and the Pacific Northwest). The largest system is owned by the City of Los Angeles with a load of 4750 MW and the smallest have peak loads less than one MW.



Scheme 1.

Power supply for the smaller systems is usually purchased from a neighboring private or cooperative utility on a rate schedule that may include both a firm contract for power, to which both the seller and buyer are committed, and 'partial requirements' of varying power supply which may fluctuate as load and other factors vary. Many public power systems generate some of their own power, for instance, with peaking turbines or diesel engines to reduce the higher cost peak load purchases.

The municipal utility is managed by a utility staff, with oversight by an elected city council, or an elected or appointed governing board. As entities of a political subdivision, the management of a public power utility is likely to be influenced by citizen, political and technical considerations, as well as economic factors. Many public power systems have responsibility for more than electric sales, including gas, water, sewage and even cable TV.

Joint action agencies, such as the Municipal Electric Authority of Georgia, have been created in many regions of the country to allow smaller public power systems to meet power supply needs collectively. A joint action agency might represent 5 to 60 systems, in a single state, and have a peak load of several hundred megawatts or more. They are large enough to build their own generating capacity, and many do. They usually do not own the transmission system that connects their widely dispersed membership. As organizations formed and supported by individual member utilities, joint action agencies are more likely to be influenced by economic and risk management factors and interest in self-dependence than public acceptance and political factors. Oversight is by a 'utility-knowledgeable' board.

Public power decision-making

A workshop for APPA was conducted by George Mason University, Center for Interactive Management, in Fairfax, VA, to explore factors that would impact a fuel cell market penetration strategy. The two-day session involved invited public power guests with an interest in their own electricity generation. The objectives were to identify and set priorities among factors influencing decisions regarding self-generation and to identify barriers inhibiting the purchase of self-generation technologies.

Several expected utility factors emerged as important:

- Financial and cost considerations
- Impact of rates to retail customers
- Reliability

But, several decision factors, possibly more important to public power systems than other utilities, also emerged:

- Political and public acceptance
- Environmental concerns
- Site availability
- Control of own destiny

The traditional factors for evaluating generation additions — *cost and risk* — are important to public power. Experience in working with the utilities participating in APPA's recent fuel cell demonstration project development efforts, however, suggested two important characteristics of these factors in the public power market.

(1) Certain public power systems may be willing to pay more for fuel cells than traditional economic comparisons would suggest. They value the environmental and operating features quite highly, including the relatively small size offered by fuel cells.

(2) The risk that many smaller public power systems are able to accept in deploying a new technology like fuel cells is relatively low. A fuel cell power plant of 10 to 50 MW may comprise such a large part of their capacity requirements that its performance must be highly reliable, even for early units.

Public power needs, or at least desires, new generation owned by municipal or joint action agency organizations. The deregulated direction that the U.S. electric utility industry is taking may provide a more competitive utility business, on the one hand, and more difficult inter-utility business transactions on the other. This trend, plus the traditions of public power, argue for replacing power purchases with self-generation if the costs and other factors tilt decision-makers in that direction.

Fuel cell features of interest

The interest of municipal electric systems in the fuel cell evolves from its numerous attractive, and unique combination of, features.

Size. At one to 50 MW, no other technology offers such high efficiency. This technology is sized to meet the smaller capacity requirements of public power.

Part load efficiency with fast response. Many systems desire a technology capable of economic operation in a broad, intermediate duty range, possibly to include baseload operation under certain circumstances.

Cogeneration potential. Many municipal systems will prefer cogeneration installations to increase public acceptance and the initial economics. Fuel cells are easier to site than other cogeneration technologies.

Environmental attractiveness. Urban power systems with generation within their boundaries will increasingly require very clean technologies. The lack of significant water requirements by fuel cells is also a real plus in a significant portion of the U.S.

Low noise. City-sited power plants must have noise characteristics that make them unobtrusive neighbors.

Short lead time and modularity. This adds up to building the capacity very close to the time that you need it. This is a real strategic benefit.

The reasons for utility and joint action agency interest offer significant insights that lead to the methodology for assessing the market.

- Certain utility characteristics seem to favor fuel cells, but the reasons for being an advocate or a leader vary significantly from utility to utility.
- Some municipal systems would prefer to own both peaking and intermediate supply capability, and they expect to continue to purchase baseload capability, often because of its low cost. Others, however, *do* foresee a baseload dispatch mode for fuel cells, especially with cogeneration.
- The desire for self-generation is rooted in interest in controlling one's future, particularly controlling costs.
- Systems that view themselves as environmentally constrained, today or eventually, are the most likely potential buyers of fuel cells. Some of these systems believe it is the *only* technology that they could build on or near their system.
- The first buyers will be manager-advocates with a vision of the future into which this technology fits. The boards or city councils will share at least the key elements of their vision.
- Joint action agencies appreciate that this technology has the size and other characteristics such that it can be sited at individual member systems. Therefore, in addition to its other advantages, fuel cells may reduce the need for transmission capacity linking their cities.

The potential of fuel cells to break through the efficiency barriers now being met by all conventional generation cannot be overemphasized. As a developing technology, fuel cells should see significant efficiency improvements. Over the next 15 to 20 years, more advanced fuel cell designs such as molten carbonate and solid oxide may be able to demonstrate efficiency improvements in the order of 50% or greater.

The fuel cell's competitors, on the other hand, including gas turbines and internal combustion engines, are at a mature stage of development. Small incremental improvements are the most that can be expected from these technologies. And improvements in conventional technologies will come at the expense of higher operating temperatures and, therefore, greater nitrogen oxide air pollution.

The market potential in public power is large

The quantification of the market focuses on three applications:

(1) additions to meet load growth requirements

(2) replacement of retired generation

(3) replacement of purchased power contracts

It is this third factor that is relatively unique to public power. It is the independence from purchased power that most strongly drives public power interest in fuel cells.

The period of interest is from 1996, the earliest date when fuel cells may reasonably be expected to be commercially available, to 2010, a date by which more advanced technologies may be considered.

The absolute market potential appears to be about 89 000 MW in the 1996 - 2010 study period. The estimated maximum market potential, or technical market, utilizing conservative values for key parameters (load growth and maximum dependence on a single technology), is 37 000 to 44 000 MW over the 15-year period. Nearly 40% of this market is outside of the largest 20 utilities. Although, many public power systems are small, 93% of the public power market can be met with a unit size no smaller than 10 MW.

Of the 37 000 to 44 000 MW maximum market potential, 14 000 to 17 000 MW is considered to be the conservative estimate of the 'potential early market.' These are utilities

(1) Whose rates are lower than the neighboring large utility, thereby giving some room for purchase of a higher-cost supply resource

(2) That are located in an air quality or water availability constrained area

An additional screening, to isolate utilities having an interest in self-generation or having existing generation, yields the 'likely early market' of 28 000 to 30 000 MW, utilizing base case values for key parameters. The more conservative parameter values yields a 12 000 to 14 000 MW market. Even this lower market estimate would provide an ample base for early market development.

Other factors may also play a role in the early fuel cell market within municipal systems.

- Transmission constraints faced by public power encourage development of self-generation over purchases.
- Interest in using the power plant as a cogenerator may have a positive or negative impact on fuel cell commercialization, depending upon whether the utility or thermal-user owns it.
- The risk of early units — technical, financial and strategic risk — must be born to some extent by the buyers and the seller. Public power has indicated a willingness to accept some of this risk, but very small systems may not be able to.

- Natural gas pricing and availability is not expected to adversely impact fuel cell commercialization, although long-term gas contracts or partnerships with the gas supplier may overcome any concerns that do exist.
- Global warming and other environmental concerns have heightened overall sensitivity to environmental issues and may have an impact on local issues.

Screening curve analysis of phosphoric acid and molten carbonate fuel cells, in competition with purchased power and the generating technologies that are available to smaller systems, indicate that a capital cost below $1100/kW (1989 $) will be necessary to achieve a sizeable mature market. Phosphoric acid fuel cells may not reach a price this low, but this is within the range of expectation for molten carbonate fuel cells. Solid oxide fuel cells also offer the promise of low capital cost and high efficiency but were not considered in this analysis.

The path to a mature product at a mature cost begins with a high-cost product. Competition with alternatives, and numerous factors affecting the early market determine the size of the expanding production base and the magnitude of declining product costs. Utilities constrained by environmental factors or size were examined separately to allow for the more limited competition that the fuel cell will see in these segments.

The results indicate that phosphoric acid fuel cells can achieve a mature market of almost 1200 MW/year at a cost of about $1100/kW. Public power is not a sufficient market to drive the costs lower. Therefore, phosphoric acid fuel cells may have difficulty competing in unconstrained public power systems. The addition of other potential markets — private utilities and others — could help to lower capital costs and thereby increase the market share of phosphoric acid fuel cells within public power.

Molten carbonate fuel cells appear more attractive, achieving a market of almost 2000 MW/year at a cost of $925/kW. Public power is sufficient for a production volume that might yield competitive costs, but even molten carbonate fuel cells will be unable to compete well with combined-cycle in unconstrained markets without a much larger market from other utilities or users.

Of course, conventional alternatives to fuel cells may, themselves, face more stringent environmental performance standards. As the costs of power from conventional alternatives may climb, the cost-competitive thresholds for fuel cells would also rise. This change in competitive position would lead to either higher capital cost thresholds for fuel cells to achieve the market levels noted above, or would lead to larger markets at the original thresholds.

Forward pricing of fuel cells, where the initial price of the product is lower than initial production costs, may be necessary to establish the market share that fuel cells are capable of attracting.

Public power presents a significant mature market for fuel cells but the real opportunity is in matching the unique needs of many public power systems to the early market needs of the manufacturers. Benefits to both public power and to manufacturers will accrue if both proceed to develop this opportunity.

Conclusions

Public power systems provide only 15% of the electricity sold in the U.S., but they can provide a market for fuel cells of 1000 to 2000 MW per year over the first 15 years of fuel cell commercialization. With their current need for a technology like fuel cells, and with the knowledge that they can provide a significant early market, APPA has asked interested fuel cell developers to present a viable demonstration and market entry program for their consideration. The opportunity presented is one of a collaborative effort to push through the early market obstacles.

The recent market study [1] for the Electric Power Research Institute and APPA concludes that a technology likely to yield a competitive product ($1100/kW 1989 $), promoted by a supplier capable of supporting product guarantees in the early commercialization stages, will have an eager market in public power systems.

The future of fuel cells for power production, therefore, is bright. Technology is ready for commercial-scale demonstrations. At least some of the fuel cell technologies offer the promise of electricity produced at competitive costs. The future will require the characteristics of fuel cells for power production. And today, in Europe, Asia and North America, there are constrained areas that can provide the market for early commercialization steps.

The long-term opportunity exists. The short-term need exists in certain market niches. In the U.S. it is in the public power sector of the utility industry. What remains to be developed is one or more collaborative buyer/seller commercialization programs that push through the near-term obstacles.

References

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2 American Public Power Association, *Notice of Market Opportunity for Fuel Cells*, Oct. 1988.