Program on Technology Innovation: Status and Prospects of Automotive Proton Exchange Membrane Fuel Cells

Study Summary

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This is an EPRI Technical Update report. A Technical Update report is intended as an informal report of continuing research, a meeting, or a topical study. It is not a final EPRI technical report.

NOTE

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ABSTRACT

After more than 20 years of massive efforts to develop automotive proton exchange membrane fuel cell (PEMFC) technology, producers of fuel cell electric vehicles (FCEVs) are beginning to offer these vehicles for sale in small numbers. As a result, it is now necessary to better understand the prospects for eventual introduction of market-competitive FCEVs in sufficiently large numbers to impact the energy supply planning of electric utility companies for the next 5–10 years and beyond.

This state-of-the-art technology update examines the prospects for automotive PEMFC technology to 1) meet the performance and life requirements for automobile propulsion and 2) be manufactured at costs and in volumes needed to make FCEVs a viable alternative to internal combustion engine powered cars within the foreseeable future. The update concludes that automotive PEMFC technology has made great strides over the past 10–15 years and has attained competitive performance, but the technology still does not meet the combination of low cost and long life required for broad commercial viability.

Uncertainties remain concerning the ultimate potential of PEMFC technology, widespread availability of cost-competitive hydrogen fuel, market segment fit, and overall market potential of FCEVs. Such issues are likely to defer commitments to substantial expansion of PEMFC component, stack, and system manufacturing capacities. As a consequence, the beginning of PEMFC mass production is unlikely to occur before the mid-2020s at the earliest—and then only if all technology life and cost issues are positively resolved and necessary production commitments are made within the next 3–5 years.

Keywords
Proton exchange membrane fuel cell (PEMFC)
Fuel cell electric vehicle (FCEV)
FCEV production
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PRIMARY AUDIENCE: Utilities

SECONDARY AUDIENCE: Stakeholders in proton exchange membrane fuel cell (PEMFC) development and commercialization

KEY RESEARCH QUESTION

Recent advances in the development and introduction of automotive PEMFCs have greatly increased the need for timely information that will help EPRI members understand whether the basis now exists for the large-scale introduction of fuel cell electric vehicles (FCEVs). It will also be important to understand whether market-competitive FCEVs are likely to be introduced in sufficiently large numbers to impact the energy supply planning of electric utility companies in the next 5–10 years and beyond.

RESEARCH OVERVIEW

This study examines the technical and cost status and the prospects of automotive PEMFC technology against generally accepted targets for FCEV market success. The study specifically considers the outlook for establishment of large-scale manufacturing of FCEVs, a second prerequisite for broad market success and energy system impact. In a first-cut effort, the study involved review of non-proprietary information published in the technical literature, presented in technical conferences, and acquired from organizations engaged in development and fabrication of PEMFC components and systems as well as complete FCEVs.

KEY FINDINGS

- After decades of massive research, development, and engineering (RD&E) by a number of developers, PEMFC stack power density—the key performance measure—now exceeds 3 kW/L, well above the U.S. Department of Energy (DOE)-industry target for early commercial stack technology. Driven by the need to reduce costs, ongoing efforts are achieving further increases, with 4 kW/L likely to be achieved in the next generation of this technology (Section 2).
- Stacks developed by original equipment manufacturers (OEMs) have demonstrated more than 3000 hours of life in tests simulating practical operation, approaching, and in at least one case exceeding, the DOE 5000 hour target considered to be the equivalent of 150,000 miles of vehicle operation. However, these stacks use electrodes with platinum-based catalyst loadings several times higher than the levels needed to meet cost targets (Section 2).
- The $30–$40/kW DOE-industry specific cost target for economically competitive PEMFC systems is highly challenging. Recent engineering cost estimates for state-of-the art systems exceed this target by 50–80%, and projections for mass production of a German stack technology using components from industrial suppliers exceed the DOE stack cost target by 100%. OEMs have not disclosed their current or projected PEMFC stack and systems costs, but these costs remain an acknowledged key issue for the commercial introduction of FCEVs (Section 2).

- Increasing stack power density and reducing the platinum content of PEMFC electrodes offers the greatest potential for stack and system cost reduction, limited however by the minimum catalyst loadings required for adequate electrode and stack life. Independent experts tend to disagree as to whether technology breakthroughs are still required to achieve the combination of low cost and long life for electrode catalysts—the first prerequisite for competitive automotive PEMFCs (Section 2).
- Other prerequisites for achieving acceptable PEMFC costs are the development and implementation of low-cost mass manufacturing methods for every PEMFC component and subsystem and for systems assembly. Present manufacturing capacities appear sufficient for annual production of approximately 6000 FCEVs, about 1–2% of true mass production. OEMs can be expected to expand the production of mechanical PEMFC components rapidly. However, the investments needed by other industries in mass manufacturing facilities for the electrochemical components (membranes, membrane-electrode assemblies, and carbon-based electrode support and gas diffusion layers) are unlikely to be made without major OEM commitments (Section 3).
- Uncertainties about the ultimate life and cost potential of PEMFC technology and remaining serious concerns about widespread availability of cost-competitive hydrogen fuel are likely to defer commitments for major expansions of PEMFC component, stack, and system manufacturing capacities by several more years. As a consequence, the beginning of PEMFC mass production is unlikely to occur before the mid-2020s at the earliest—and only if all technology life and cost issues are positively resolved and the necessary production commitments are made within the next 3–5 years (Section 4).

WHY THIS MATTERS

This report provides the utility industry with an independent assessment of whether automotive PEMFC technology and FCEVs are likely to become a commercially successful, mass-produced transportation option that could impact the energy supply plans of utilities during the coming 10–15 years and beyond. Readers will gain an understanding of the current status of PEMFC technology and the key issues that still need to be resolved if FCEVs are to become successful on the scale envisioned by some OEMs and regulatory agencies.

HOW TO APPLY RESULTS

Utility personnel can use this document to help them decide whether and how to engage in information, planning, and business activities involving FCEVs as part of expanding electric transportation.

LEARNING AND ENGAGEMENT OPPORTUNITIES

- Key references on PEMFC technology and costs as well as comparisons of FCEVs with battery-powered EVs are appended to this document.
- Significant engagement opportunities exist with staffs of public utility commissions, California Air Resources Board, California Energy Commission, and other regulatory agencies such as air quality management districts (AQMDs).

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FOREWORD

Utilities large and small serve as their customers' trusted energy advisor for complex issues ranging from energy efficiency to solar and other renewables to demand response programs and transportation. On transportation, utilities across North America have gained firsthand experience through their vehicle fleets, conducting demonstrations of alternative fuels including natural gas, electricity, and hydrogen. These trials have served as important real-world tests and have informed utility understanding of the opportunities and challenges each fuel presents. Importantly, these trials have enabled utilities to pass along the knowledge to their customers, thereby enhancing the trusted advisor role.

Today, some fuels and technologies have advanced beyond demonstration to commercialization. Natural gas currently provides an alternative to diesel for some medium- and heavy-duty vehicles. Plug-in electric vehicles (PEVs) are a growing component of the passenger vehicle market. Since late 2010, in fact, more than 604,000 PEVs have been sold in the United States.

Another new technology is entering the marketplace in limited numbers and locations. Over the last two years, three automakers (Hyundai, Toyota, and Honda) have begun to introduce hydrogen fuel cell electric vehicles (FCEVs) to consumers. Unlike natural gas and PEVs, which have reached early market commercialization, FCEVs remain in the pre-commercial phase. Are FCEVs a viable alternative to traditional gas- or diesel-powered vehicles? Some auto manufacturers believe they can be.

While preparing to educate and support customers, utility leaders may ask a number of questions about FCEVs such as the following:

1. How close are hydrogen fuel cells to meeting cost, durability, and performance goals established by the U.S. Department of Energy?
2. What is required to manufacture hydrogen fuel cells at scale?
3. How will the hydrogen fuel be made, stored, shipped, and distributed to the driving public, and when will it become cost-competitive with other fuels?
4. In light of the current technical performance of hydrogen fuel cells in vehicles and requirements to manufacture the fuel cells at scale, when might utilities reasonably expect FCEVs with comparable life, cost, and performance to be commercially available to their customers?

The answers to these questions will help utilities understand the basic question their customers may ask: What is the status of hydrogen fuel cells and are they viable for me?

This white paper presents a systematic review of the performance and cost of hydrogen fuel cells, using information collected in direct interviews with the global leaders in hydrogen fuel cell technology within the automotive industry. The paper aims to educate utility leaders on the status of hydrogen FCEVs as alternative transportation for the mass market so that utilities can, in turn, best prepare and prioritize their efforts to serve their customers.

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1
INTRODUCTION AND SCOPE

Recent progress in the development and introduction of automotive Li Ion batteries and Proton Exchange Membrane (PEM) fuel cells has greatly advanced the prospects for widespread electrification of transportation. This has increased the need for timely information that will help EPRI members position themselves for the challenges and opportunities that are coming with these developments.

EPRI has continued to review and communicate the advances in battery technology and consequent emergence of plug-in hybrid electric vehicles and purely battery-powered vehicles in the personal transportation market. The need is now to better understand whether the advances in PEM fuel cell technology are providing the basis for the large-scale introduction of fuel cell-powered vehicles, and whether – and, if so, when – market-competitive fuel cell electric vehicles (FCEVs) are likely to become introduced in large enough numbers to impact the energy supply planning of electric utility companies for the next 5-10 years and beyond.

After more than 20 years of massive efforts developers and prospective producers of FCEVs are now giving encouraging answers to these questions. However, they are still being debated between knowledgeable advocates and skeptics of FCEVs. At the time of this writing publicly available information is inadequate to confidently answer whether:

- PEM fuel cell (PEMFC) technology will have the combination of performance, endurance (life), and cost characteristics required to make FCEVs competitive with conventional automobiles,
- PEMFC manufacturing capacities required for mass production of competitive FCEVs can be established within the next ten years, and
- whether hydrogen production, distribution, and delivery infrastructures can be established in time to supply PEMFC-powered electric vehicles with cost-competitive fuel.

The present study addresses the first two of these questions: it examines the technical and cost status and prospects of automotive PEMFC technology against generally accepted targets for market success of FCEVs, and it considers the outlook for establishment of large-scale manufacturing of the technology, a second prerequisite. The third prerequisite for market success – widespread availability of an adequate supply of hydrogen at competitive cost – presents a series of challenges some of which may be examined in separate EPRI studies.

This study is a first-cut effort, based on non-proprietary information published in the technical literature, presented in technical conferences, and acquired from key information sources including companies engaged in development and fabrication of PEMFC component and system technology and of complete FCEVs. All sources that provided information in response to EPRI's solicitation were given the opportunity to critically review drafts of the study summary; their comments are reflected in this document. However, some of the leading FCEV developers and prospective manufacturers have chosen not to provide information, or to comment on this summary.

2
AUTOMOTIVE PEM FUEL CELL TECHNOLOGY

Background

Fifty years ago the first efforts to develop fuel cells into automotive power sources were doomed by the excessive weight and volume of the alkaline-electrolyte fuel cell technology selected for development, and by the unrealistic choice of cryogenic oxygen to avoid electrolyte carbonation by CO_2 in the oxidant air. Ten years later research (primarily at the Los Alamos National Laboratory) on hydrogen-air fuel cells with carbon dioxide-tolerant proton exchange membrane (PEM) electrolytes laid the groundwork for four decades of PEM fuel cell (PEMFC) development that made fuel cells candidate power sources for automobile propulsion.

Daimler was the first automobile OEM to enter this development in the early 1990s teaming with Ballard, followed by Toyota, Honda, Hyundai and others. After expenditure of several billion dollars, and supported by multi-$100 million Government-funded RD&D programs in the US, Japan, and Europe (especially in Germany), OEM efforts have now led to prototypical and early production FCEVs that are demonstrating adequate performance and good drivability. The PEMFCs powering these vehicles meet some but not all of the requirements for commercial competitiveness. The most important of these requirements have been translated into targets that are reviewed below, together with the prospects for their attainment within the coming 5-10 years.

Technical and Cost Targets

Targets for the development of automotive PEMFCs were first set two decades ago by DOE in close collaboration with the US OEMs that had become engaged in automotive fuel cell development. The most important of these targets are derived from the minimum levels of system performance and endurance required, and the maximum capital costs acceptable, for FCEVs to begin entering the personal transportation market. Targets were revised periodically to reflect perceived changes in requirements (for example, for higher performance) and to take into account technology progress.

Table 2-1 shows the current targets for PEM fuel cell stacks and complete power systems, taken from the DOE June 2013 Technical Team Roadmap document. The table also includes data on the current status of stack and system technologies. Based on publically available information (primarily from DOE-funded RD&D) the status data reflect the judgement of the USDRIVE Collaboration’s Fuel Cell Technical Team.

Table 2-1
Automotive Fuel Cell Technology Targets[1]

Characteristic	Units	Fuel Cell Stack[2]				Fuel Cell System[3]			
		Target		Status	Projection	Target		Status	Projection
	Years	2020	Long Term	2013	>2020	2020	Long Term	2013	>2020
Power Density	kW/L	2.5	2.5	3	4	0.65	0.85	0.65	>0.85
Specific Power	kW/kg	2	2	2	?	0.65	0.65	0.65	>0.65
Efficiency	%[4]	65	-	65	65-70	60	70	60	?
Endurance	Hours[5]	5,000	8,000	2,500	?	5,000	8,000	2,500	?
Specific Cost	$/kW	20	15	24	?	40	30	55	?

[1] Targets also have been set for a number of other automotive fuel cell stack and system characteristics but those in Table 2-1 are considered the most critical for commercial viability of FCEVs.
[2] Includes membrane-electrode assembly (MEA), bipolar plates, stack hardware, and assembly; excludes balance of plant (BOP) and thermal control system (TCS).
[3] Includes stack, BOP, and TCS; excludes H2 storage, battery, electric drive system, and power electronics.
[4] Percent at 25% of peak power.
[5] For PEMFC stacks with comparatively low levels of platinum-based electrode catalysts.

Status, Challenges, and Prospects

The data in Table 2-1 indicate that even after decades of very large RD&E efforts stack life and cost do not yet meet critical endurance and cost targets. Increasing PEM stack performance above current targets also remains an important goal and challenge inasmuch as increases of stack specific performance translate almost directly into urgently needed reductions of specific costs.

Performance

Stacks

DOE's original performance targets were derived from the requirement that a rather low power (50kW) fuel cell system could be accommodated on a representative mid-size automobile; this requirement translated into a stack power density target of approximately 1kW/L. Since then system total power requirements were increased to more realistic levels, first to 80kW and then to 100-120kW (the Toyota Mirai has 114kW). To retain adequate levels of vehicle performance and space utility the DOE targets for stack and system performance had to be increased to the levels shown in Table 2-1 which greatly increased the technical challenges for PEMFC stack and system development.

Continuing refinements of electrode catalysts, MEAs, and gas diffusion and distribution layer structures have lowered cell kinetic, ohmic, and diffusion resistances to permit substantially increased cell current densities and stack power densities. Toyota and Honda claim achievement of more than 3kW/L, and the German consortium ASC ("Auto Stack Core") expects to reach 3.8kW/L in 2016/2017, with 4kW/L considered achievable, also by Daimler.

The power densities achieved to date already exceed DOE targets but further increases are being pursued to reduce stack specific cost. Although these efforts are facing increasingly difficult technical challenges – such as utilization of thinner but still robust membranes, and development of yet more efficient and durable catalysts – at least one leading developer stated that improvements are occurring faster than projected by DOE. However, at present no stack power density projections beyond 4kW/L have been made public.

System

In the estimate of the DOE Fuel Cell Technical Team the near term targets for fuel cell system power density have been achieved (Table 1). OEM data to quantitatively substantiate this claim are not available but in the Toyota Mirai and the FCEVs of other OEMs the system apparently fits in the motor compartment equivalent of ICE vehicles. Further increases in PEMFC stack and system power density, presently driven mainly by cost reduction pressures, will help offset the volume and weight of the hydrogen storage and battery subsystems of future FCEVs.

System Total Power

Approximately 100-120kW appears to be the power level OEMs have reached in their prototype and early commercial FCEVs. Although about twice the past target, this power level still is around 40% lower than the peak power average of today's US mid-size cars, SUVs, and light trucks.

While early users of prototypical FCEVs appear to be satisfied by their performance it is unclear whether future average owners/users of FCEVs will consider 100-120kW fully satisfactory. If OEMs ultimately have to aim for higher FCEV power levels this will exacerbate current cost issues.

Endurance

A minimum life requirement of 10-15 years and ≥150,000 miles with no more than 10% performance degradation is generally accepted for FCEVs and other advanced-technology vehicles. At an average speed of 30mph 150,000 miles translates into 5000 hours of operation, the current nearer-term target (Table 1) for fuel cell system and thus also stack endurance under representative operating conditions. For life testing purposes, such conditions are being simulated in the U.S.DRIVE Fuel Cell Technical Team (FCTT) cycle that has been developed by DOE to test stack endurance; the 2,500 hour endurance in Table 1 is typical for stacks with electrodes of acceptably low loading with platinum-based catalysts.

Some OEM-developed stacks have demonstrated more than 3,000 hours in this type of test, and at least one prototypical FCEV has been driven more than 190,000 miles in more than 6,000 hours of operation.

However, the stacks used in these tests and demonstrations have electrodes (particularly air cathodes) with platinum-based catalyst loadings 2-3 times higher than the levels considered acceptable to meet cost targets, see the Cost section below. It is generally assumed that this is true also for the stacks used in the prototypical and early commercial FCEVs of other OEMs, and for the stacks of PEMFCs that have demonstrated up to 20,000 hours life in certain bus applications. Pre-prototype stacks with acceptably low anode catalyst loadings developed by the German consortium ASC have delivered well over 3,000 hours in generic drive cycle tests.

To attain the needed fuel cell stack life is highly challenging because PEM fuel cell electrodes and stacks can degrade in several ways all of which have been shown to reduce performance over time; these are summarized in Table 2-2.

Table 2-2
Life-Limiting Processes in PEM Fuel Cells

Problem	Mechanism	Impact	Mitigation	Status
Loss of Catalyst Surface Area	Catalyst dissolution, recrystallization, and/or detachment from support	Loss of cell and stack efficiency and power	Catalyst stabilization by alloying, support modification, etc.	Not fully resolved; RD&D continuing
Loss of catalyst support	Electrochemical corrosion (oxidation) of carbon catalyst supports at high electrode potentials	Loss of cell and stack efficiency and power	Improved controls to limit damaging cell electrode potential and gas conditions	Not yet clear to which level problem can be reduced in actual stack operations
PEM degradation	Membrane material de-polymerization; mechanical damage in thermal cycling	Thinning of membrane; local electrical and/or chemical shorts	Membrane chemical and mechanical stabilization	Problem probably resolved with advanced PEMs

The main problems – catalyst active surface losses, and catalyst support corrosion – not only have multiple causes but become more serious under high-stress operating conditions such as frequent start-ups and shut-downs, and voltage cycling. Degradation processes also become more pronounced at low loadings of electrodes with catalyst, primarily because such electrodes have a lesser “reserve” of catalyst to offset degradation effects.

R&D has identified several approaches to increasing the activity and extending the life of catalysts. However, the translation of these and future advances into substantial advances in stack technology remains a lengthy process because of the multiple, complex interactions between the various parameters that control the activity and stability of the membrane (catalyzed) electrode assembly (MEA) and the performance and life of complete cells and stacks. Reducing the thickness of the PEM membrane (to reduce cell and stack resistance, increase peak power and thus reduce per-kW costs) introduces yet another complicating factor and increases the probability for PEM degradation to become a longer-term problem.

Clearly, achieving at least 5,000 hours life for fuel cell stacks capable of the required high power densities but limited to economically feasible amounts of catalysts (see below) still poses very difficult challenges. The OEMs engaged in the development and introduction of FCEVs acknowledge these difficulties and are devoting major efforts to overcome them.

Cost

Driven by the goal of fuel cell competitiveness with IC engines the DOE stack and system specific (i.e., per kW) cost targets for mass-produced systems (see Table 1) are highly ambitious: $30-$40/kW is less than 1/10 of the cost targets for other applications of PEM fuel cells, or for other fuel cell types. Remarkably, the $55/kW cost status number in the table suggests that attainment of automotive fuel cell cost targets may be within reach. However, the status data in Table 1 are calculated numbers only based on engineering cost models for technology and mass production.

Probably more meaningful are the cost data for an approximately 100kW PEM stack currently being developed by the ASC consortium that are based on real stack technology using key components fabricated by the industrial members of the consortium. ASC's current (Evo 1) stack is estimated to cost about $50/kW if produced at the 30k stacks/year rate. The next generation (Evo 2) stack is projected to cost $37/kW if produced at 30k stacks/year, still almost twice the $20/kW DOE target for a 500k stacks/year production rate. Scaling ASC's $37/kW stack costs by a factor 2 (the approximate ratio of DOE's detailed system-to-stack cost projections) results in projected system costs of about $75/kW, almost twice the DOE near term (and more than twice the longer term) target for an automotive fuel cell system. Applying a modest estimate of 35% for overheads and profit to $75/kW results in about $100/kW specific cost, for a fully loaded cost of about $10,000 for a ~100kW system. Adding an estimated $3,000 for the costs of the hydrogen storage, battery and power electronic subsystems results in approximately $13,000 for a complete PEM fuel cell power plant.

Because costs of this magnitude are unlikely to be competitive in a future mass-market, there are large pressures to reduce PEM fuel cell stack and systems costs to – preferably even below – the DOE targets. This need translates into cost reduction pressures for every component of the stack, especially the PEM membrane itself and the platinum-based catalysts that together make up more than half of mass-produced stack costs. In particular, catalysts are the major cost contributor: at a typical 1W/cm^2 power (area) density each 0.1 mg/cm^2 of catalyst loading adds approximately $5/kW to stack costs, assuming a nominal platinum price of $1,500/oz. The DOE cost status estimates assume 0.2-0.3 mg/cm^2 loading, but the minimum platinum levels required for adequate stack endurance are not yet established. At 0.6 mg/cm^2, a loading typical for state-of-the-art stacks that approach endurance targets, platinum cost is approximately $20-30/kW for the likely $1,000-1,500/oz platinum price range. For a 100kW stack this results in an estimated platinum cost contribution of $2,000 to $3,000, far above target.

R&D has achieved adequate performance at substantially lower platinum catalyst loadings, but achievement of long life at low loadings continues to prove elusive. Severe cost pressures also exist for all other stack and BOP components, especially bipolar plates and gas diffusion layers, the air supply system, and the various water and coolant loops.

All of these technology cost reduction needs are being addressed in the PEMFC development programs of the OEMs and prospective suppliers of stack and system components. Several OEMs have stated that present technology does not meet cost targets but is expected to do so with continuing technology development and transition to mass production. Unfortunately, however, almost no information on current or projected PEM fuel cell stack and systems costs is available from the OEMs. As a consequence it is not possible to assess with confidence where

OEMs are at present on the highly challenging path to cost-competitive automotive fuel cells, and whether – and when – competitive costs might ultimately be attained for technology that also meets endurance targets.

Independent experts tend to disagree whether technology breakthroughs are still required to achieve the needed combination of low cost and long life for electrode catalysts. There is agreement on the second prerequisite: the development of low-cost mass manufacturing methods, and the achievement of true mass production, for PEMFC components, subsystems, and systems. Whether the ongoing, large efforts of the OEMs will result in fully competitive PEMFC and FCEV technology without further technical breakthroughs still seems uncertain.

3
PEM FUEL CELL MANUFACTURING CAPACITY

Background

PEM fuel cells have entered first markets, primarily in stationary power generation, with worldwide shipments of 180MW (in the US 140MW) in 2014 and continued rapid growth expected. However, these applications pose far less demanding requirements for low costs and high performance than the automotive power source application. Accordingly, the technology solutions and production capacities developed for these applications are not generally applicable for the manufacturing of PEMFCs for automobile propulsion.

PEMFCs have been used for a decade as power sources for electric buses operated in test fleets, and this application is gaining momentum in the US, China, and Europe. However, delivered bus PEM fuel cell system capacity is still only about 30MW/year worldwide, and current technology probably does not directly qualify for automobile applications. On the other hand, PEMFC technology – especially PEM stacks – that would meet the stringent requirements for automobile applications might well lend themselves to bus and other large vehicle applications. Accordingly, successful development of automotive PEMFC technology can be expected to enable or accelerate applications in the propulsion of heavy vehicles that, in turn, might be able to serve as test beds and early market niches for the automotive technology.

Status, Challenges, and Prospects

Industry insiders estimate that today's total automotive PEMFC manufacturing capacity is around 6,000 systems (approximately 500-600MW) per year, with most of it established by Toyota, Hyundai, Honda, and Daimler. While several times larger than non-automotive PEMFC production capacity 500MW/year is approximately two orders of magnitude below the levels at which FCEVs would begin to make significant energy system impacts within the planning horizons of electric utilities or cause emission reductions of the magnitude sought by the organizations charged with attainment of mandated air quality and greenhouse gas emission targets.

Several OEMs have stated their intent to offer FCEVs for the personal transportation market in the 2020s, and it can be assumed that the leading OEMs are engaged heavily in the development of processes and plant concepts for mass-manufacturing of automotive PEMFC stacks and systems. The DOE-funded engineering cost estimates indicate that a production rate of 30k stacks per year would be required to reduce specific costs to approximately twice of true mass production costs. However, at this time no plans for rapid expansion of automotive PEMFC manufacturing capacity even only to this "volume manufacturing" level have been announced by OEMs.

This raises the question whether and how the expansion to true mass production can be realized, given that it would require a 50% increase in capacity each year for 10 consecutive years to increase current PEMFC production capacity to e.g. 500k PEMFCs (and FCEVs) per year by 2027, with the implication that corresponding manufacturing capacity increases would need to be established for every component of the fuel cell system. OEMs (including their current suppliers) should be able to accomplish this expansion for the production of bipolar and cooling plates and the various BOP components because of their expertise in the development and establishment of mass production processes for mechanical components. However, as industry insiders have noted, the establishment of facilities for high-quality, low-cost mass manufacturing of the critical "electrochemical" stack components – PEMs (membranes), MEAs (membrane-electrode assemblies), and carbon-based gas diffusion and distribution layers – could become the controlling factors for the rate of expansion of PEMFC production capacities.

Focusing specifically on the membrane, the central element of PEMFCs, existing facilities at several US and international producers of fluorochemicals probably are sufficient to supply PEM precursor ionomer and membranes for several 10,000 stacks/year. For example, discussions with Chemours, the manufacturer of Nafion™ PEM membranes and a leading PEM supplier, established that manufacturing capacities could be expanded within 2-3 years to supply much larger quantities given a sound business case, i.e. commitments by OEMs or MEA manufacturers. However, PEMs are still being optimized for the different designs and operating requirements of the stacks under development and in low-volume production by prospective manufacturers of PEMFCs. Significant changes in membrane specifications will require requalification for the intended application and are likely to extend production lead times to at least 3-5 years from the time of commitment.

The situation is likely to be similar for MEAs for which limited-scale manufacturing processes have been established by several suppliers. These processes appear to lend themselves to rapid expansion as well, with similar implications as for PEM production: need for timely OEM commitments, and longer lead times if key product specifications (for example catalyst loadings) are changed. However, the required investments are likely to be made only after OEMs have committed to PEMFCs and FCEVs as future mass market products.

Given that stack technology advances are still being pursued by OEMs, and in view of the large number of component and subsystem technologies and their prospective manufacturers that need to come together in a competitive mass-manufactured PEM fuel cell technology, it seems more than likely that establishment of PEMFC mass production capacities will require a lead time of at least 3-5 years from the time of commitment. Moreover, remaining uncertainties about the ultimate life and cost of PEMFC technology, concerns about widespread availability of cost-competitive hydrogen fuel, and questions about the market segment fit and overall market potential of FCEVs (see below) might well defer these commitments for several more years. As a result, the beginning of PEMFC mass production is unlikely to occur before the mid-2020s at the earliest.

Additional Issues for Expansion of FCEV Production

In the course of the study two other issues were identified that seem likely to impact the prospects for expansion of PEMFCV production and market introduction of FCEVs.

Market Potential of FCEVs

Industry insiders have noted that FCEVs might not be able to capture the broad markets needed to support mass production and achieve true mass production economics. For one, PEMFCs developed primarily for mid-size automobiles might not be suitable for smaller cars because

PEMFC system volume and cost do not scale down linearly with power requirements. As a consequence current systems may prove too expensive and bulky for this market segment that is very large in Europe, only modest but growing in the USA. In the key US market segments of mid-size and full-size cars and SUVs many if not most vehicles have IC engines with 150-200kW. To be competitive FCEVs may require PEMFCs with peak power levels well above the current 100-120kW which would exacerbate the FCEV cost competitiveness issue. (This is likely to a problem also in Germany where the capability of being driven at high speed for extended periods is demanded of the larger and more expensive cars and SUVs that might otherwise be a logical market for FCEVs.)

Impacts of Delays and Competition

If the introduction of competitive PEMFCs begins to lag current OEM expectations substantially (e.g. by more than 3-5 years) the current rapid evolution and US market entry of BEVs with affordable larger batteries that enable much-increased driving ranges could impact the market prospects of FCEVs negatively: prospective buyers of FCEV might hesitate to commit, and industries and investors might become reluctant to provide the large resources required for the establishment of large-scale PEMFC component and system production capacities. This concern, expressed also by some FCEV advocates and high level OEM representatives, might affect the willingness of public and private organizations to fund the rapid expansion of hydrogen supply and distribution infrastructures needed for PEMFC-powered FCEVs.

4
SUMMARY AND CONCLUSIONS

Automotive PEM Fuel Cell Technology

Decades of worldwide, massive RD&E have enabled OEMs engaged in the development and introduction of FCEVs to achieve the PEMFC stack and system performance characteristics capable of powering today's early production vehicles. Further performance gains are being pursued by the OEMs to reduce per-kW costs and make FCEVs competitive with today's more powerful ICE automobiles. These gains will be increasingly difficult to attain because PEMFC technology must meet not only challenging cost but also difficult endurance targets.

Automotive PEMFC stacks with acceptably low levels of platinum-based electrode catalysts have not yet demonstrated adequate endurance in real life FCEV operation. Under typical operating conditions encountered in real world driving – such as frequent start-ups and shut-downs, and voltage cycling due to load changes – PEM fuel cell electrodes suffer active surface losses and carbon electrode support corrosion. These and other life-shortening degradation processes become more pronounced when loadings of electrodes with platinum-based catalysts are reduced to reduce stack and system costs. R&D has identified several approaches to stabilizing the activity and life of lightly loaded electrodes but their technical and cost effectiveness remain to be demonstrated in representative stack technology and operating environments.

At \$30-\$40/kW the specific cost target for competitive PEMFC systems is highly ambitious. Recently, DOE-funded cost analyses based on engineering models for developmental technology and projected mass production have estimated a systems cost of \$55/kW, or 50-80% above target. No current or projected PEMFC costs have been revealed by the OEMs, but for an advanced stack technology fabricated in Germany with components from industrial suppliers a stack specific cost of approximately \$40/kW in volume production has been projected. This cost translates into a system cost of approximately \$75/kW and, with appropriate overheads, a total cost of around \$10,000 for a ~100kW system. The hydrogen storage, hybrid battery and power electronic subsystems are likely to add at least \$3,000, for a complete automotive PEMFC power plant cost of around \$13,000.

Costs of this magnitude are unlikely to be competitive. Accordingly, there is continued great pressure on developers and prospective manufacturers to reduce PEM fuel cell component, stack, and systems costs. Because platinum-based catalysts contribute up to \$25-30/kW at the loadings typical for state-of-the-art stacks, reducing their platinum content has the largest potential for cost reduction, limited however by the minimum catalyst loadings required for adequate electrode and stack life. At present, this minimum level does not appear to be well established.

Independent experts tend to disagree whether technology breakthroughs are still required to achieve the needed combination of low cost and long life for electrode catalysts, the first prerequisite for competitive automotive PEMFCs. There is agreement on the second prerequisite: the need for the development and implementation of low-cost mass manufacturing methods for every key PEMFC component and subsystems, and for systems assembly. Whether the ongoing, large efforts of the OEMs in these areas will result in fully competitive PEMFC and FCEV technology without further technical breakthroughs still seems uncertain.

PEM Fuel Cell Manufacturing Capacity

Today's total automotive PEMFC manufacturing capacity is estimated to be approximately 6,000 systems per year, nearly two orders of magnitude less than the level needed to support mass production of FCEVs in the 2020s, the stated intent of several OEMs. To illustrate the challenge, establishing the capacity for manufacturing 500,000 PEMFCs per year would require a 50% increase in current capacity each year for 10 consecutive years. OEMs (including their current suppliers) should be able to accomplish this type of expansion for the production of mechanical stack and BOP components. However the capabilities for rapid establishment of facilities for low-cost, high-precision mass manufacturing of the key "electrochemical" components – PEMs (membranes), MEAs, and gas diffusion and distribution layers – by the appropriate industries are not obvious.

The study examined production capacity status and expansion prospects for the membrane, the central element of PEMFCs. Existing facilities at several US and international fluoro-chemicals producers probably are sufficient to supply membranes for 10,000 stacks/year, and manufacturing capacity probably can be expanded within 2-3 years to supply much larger quantities. Existing MEA manufacturing processes also should lend themselves to rapid capacity expansion, with increased lead times if key product specifications are changed. However, the investments required for membrane and MEA production capacity expansions are likely to be made only after OEMs have committed to PEMFCs and FCEVs as future mass market products. Despite the stated intent of several OEMs to offer FCEVs for the personal transportation market beginning now and growing to mass market volumes in the 2020s no such commitments appear to have been made. It seems more than likely that establishment of PEMFC mass production capacities will require a lead time of at least 3-5 years from the time of commitment that must be considered quite uncertain because of the combination of current uncertainties and perceived risks.

Conclusions

This study examined the prospects for automotive PEM fuel cell technology to meet the performance and life requirements for automobile propulsion, and to be manufactured at costs and in volumes needed to make fuel cell electric vehicles a viable alternative to internal combustion engine powered cars within the foreseeable future.

Its main findings are that PEMFC technology has made great strides over the past 10-15 years and attained competitive performance, but it still does not meet the combination of low cost and long life required for broad commercial viability. It is unclear whether, how, and when this essential requirement can be achieved. Uncertainties about the ultimate life and cost potential of PEMFC technology, remaining serious concerns about widespread availability of cost-competitive hydrogen fuel, and questions about the market segment fit and overall market potential of FCEVs, are likely to defer commitments to major expansions of PEMFC component, stack and system manufacturing capacities several more years. As a consequence, the beginning of PEMFC mass production is unlikely to occur before the mid-2020s at the earliest – and only if all technology life and cost issues are positively resolved and the necessary production commitments made within the next 3-5 years.

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