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Chapter 95

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1 INTRODUCTION: THE HISTORY OF FUEL CELL COMMERCIALIZATION

The concept of the fuel cell traces its roots all the way back to William Grove's famous experiments on water electrolysis in 1839, but the commercialization history of fuel cell technologies remains rather limited over 150 years later. Throughout the later part of the 19th and early part of the 20th centuries, attempts were made to develop fuel cells that could directly convert coal or some other carbon material into electricity, but these attempts were unsuccessful because scientific knowledge of material properties and electrochemistry was lacking. The first fuel cell capable of producing significant quantities of electricity was developed by Francis Bacon in 1932. This system used an alkaline electrolyte and nickel electrodes to produce electricity using hydrogen and oxygen. By 1952, Bacon had produced a 5 kW system, and this provided much of the basis for further work on fuel cells in the 1950s and 1960s.

Fuel cell development received a boost in the late 1950s, when the National Aeronautic and Space Administration (NASA) determined that fuel cell technology was the most promising option for producing electricity in space in a compact and safe fashion. Nuclear power was considered too dangerous, batteries were too heavy, and solar power was too cumbersome. NASA eventually funded over 200 research contracts for fuel cell technology, and used both alkaline and proton-exchange membrane fuel cells (PEMFCs) in the Apollo, Gemini, and space shuttle programs. The Gemini program utilized 1 kW PEMFC units from 1965 to 1966, while 1.5 kW alkaline fuel cell (AFC) units were used in the Apollo program from 1968 to 1972. More recently, three 12 kW AFC units have been used for at least 87 missions with 65 000 h flight time in the space shuttle Orbiter.[1] Altogether more than 100 manned space flights have been made by the US, totaling over 90 000 h of operating time, and all of these have used fuel cell systems developed by the United Technologies Corporation (UTC) of Windsor, CT.

The experience of UTC and its International Fuel Cells (IFC) unit with fuel cells for the space program led to the development of the first truly commercial fuel cell system, the PC25 phosphoric acid fuel cell (PAFC) product. This stationary fuel cell generating system, now in its third generation design, produces electricity from natural gas that is reformed into a hydrogen-rich gas stream before being supplied to the fuel cell stack. PC25s were first manufactured by IFC's ONSI division in 1991, and approximately 200 of these 200 kW fuel cell systems have now been purchased and deployed throughout the US and in other countries. Many of these systems were either procured under a US

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Department of Defense (DOD) fuel cell purchase program, where about 30 units were purchased and operated at US DOD facilities, or through a \$1000 kW^{-1} fuel cell purchase subsidy program also administered through the US DOD.[2]

For motor vehicle applications, General Motors has the longest history among major automakers, having experimented with fuel cell technology in the 1960s and having demonstrated the world's first drivable fuel cell passenger vehicle in 1966. General Motors designed this vehicle, called the "Electrovan", with liquid hydrogen and oxygen fuel tanks, and it achieved a range of 150 miles and a top speed of 70 miles h^{-1}. The Electrovan program demonstrated General Motors' early interest in developing fuel cell vehicles for commercial use, but it also uncovered the several obstacles that then became the focus of research and development. These included the needs for improved electronics, breakthroughs in electrochemistry, and new fuel cell stack and system materials.[3]

During the decade of the 1990s, fuel cells experienced an intense phase of research and development that led to the formation of many new companies and the establishment of new divisions within established companies, and a complex series of corporate mergers and re-organizations. Many different companies are now planning to commercialize several different fuel cell technologies for a wide range of markets. These fuel cell technologies include the PEMFC, AFC, and PAFC technologies mentioned above, but also higher temperature solid-oxide fuel cell (SOFC) and molten carbonate fuel cell (MCFC) types. A variation of the PEMFC can also use methanol directly, without first reforming it into hydrogen; it is known as a direct-methanol fuel cell (DMFC). There also is an interesting class of metal/air fuel cells that could also be considered "mechanically recharged" batteries, and that may be attractive for certain niche applications.

Fuel cells are currently being developed for the following applications:

- power for portable electronic devices (5–50 W)
- power for remote telecommunications applications (100 W–1 kW)
- power for construction and outdoor recreational uses (1–3 kW)
- auxiliary power units for cars and trucks, and motive power for scooters (3–5 kW)
- stationary power generation (1 kW–50 MW)
- electric passenger car, utility vehicle, and bus power systems (20 kW–250 kW).

Some fuel cell companies are focusing on a single fuel cell type and application combination, while other companies are investigating more than one fuel cell technology and various potential applications. The following sections of this chapter briefly describe the current state of fuel cell industries for the stationary power and transportation markets, some of the commercialization plans for these two sectors, and additional thoughts about prospects for market commercialization of fuel cell technology. We do not discuss in detail the prospects for fuel cell for portable electronic devices, since this application is rather distinct and still at a relatively early stage of development.

2 CURRENT STATUS OF FUEL CELL TECHNOLOGY FOR STATIONARY APPLICATIONS

Fuel cells are under intense development for use as distributed generation (DG) resources. DG consists of small, modular power systems that are sited at or near their point of use. Typical DG systems are smaller than 30 MW and may include such technologies as gas turbines, reciprocating engines, biomass-based generators, concentrating solar power and photovoltaic systems, wind turbines, microturbines, and flywheel storage devices, in addition to fuel cells. The advantages of DG compared with conventional large-scale power plants include the ability to capture waste heat to "cogenerate" heat as well as electrical power, reductions in transmission losses, the ability to get around transmission and distribution "bottlenecks" and to defer substation upgrades, and the ability to achieve higher levels of reliability.

In fact, the market for DG is to a significant extent aimed at customers dependent on reliable energy, such as hospitals, manufacturing plants, grocery stores, restaurants, and banking facilities. DG owned by these customers can provide peak-shaving, cogeneration, and stand-by power, and these services translate into direct customer benefits. Fuel cells can also be used in a stand-alone configuration to supply power in remote locations where grid power is not available. In addition to this customer-owned DG model, however, utility-owned DG is another possibility that can provide benefits to the utility when DG resources are installed on the utility side of the meter. These benefits include the ability to serve loads where transmission and distribution are constrained, and the ability to provide voltage support and other grid ancillary services from the DG facilities.

Fuel cell technologies being developed for use in stationary DG applications include PEMFCs, PAFCs, SOFCs, and MCFCs. In general, PEMFCs, PAFCs, and SOFCs are being developed for smaller DG applications in the 1–300 kW scale. These systems would serve the loads of individual buildings, or perhaps small groups of adjacent buildings. For larger scale applications, in the range of 300 kW–3 MW or more, SOFC and MCFC systems are being developed, with particular focus on MCFC for MW scale applications.

Stationary fuel cell systems are generally expected to run on pipeline natural gas that is either externally or internally reformed into hydrogen before being reacted in the fuel cell stack. In the external reforming process, a special fuel reformer is included as part of the system and this fuel reformer uses one of several possible methods to remove the hydrogen from the carbon "backbone" of the methane molecule. Reformer types include steam–methane reformers, partial oxidation reformers, and auto-thermal reformers, all of which differ with regard to the chemical processes used, efficiencies and capital costs. Steam methane reforming is the most mature of these technologies, having been used for commercial hydrogen production for many years, but other reformer technologies are also being developed. Internal reforming occurs in the higher temperature SOFC and MCFC types, and is the process whereby methane is reformed directly into a $H_2/CO/CO_2$ gas mixture due to the high temperatures. These fuel cell types thus do not need the complicated external reformer, and this is an advantage from a capital cost and system complexity perspective.

In addition to pipeline natural gas, stationary fuel cells could also operate on anaerobic digester gas, which contains methane in a mixture with carbon dioxide, oxygen, and nitrogen, or landfill gas that is produced naturally at landfills. They could also operate on any other fuel that can be readily reformed into hydrogen, including propane, butane, methanol, ethanol, kerosene, dimethyl ether and naphtha, among others.

A significant barrier to the use of fuel cells as stationary DG resources has been the high capital costs of the fuel cell systems that have been sold or demonstrated thus far. The IFC PC-25 200 kW PAFC units have sold for approximately \$4000 per kW, not including installation costs. Fuel cell energy has quoted costs of \$5000 kW^{-1} for its MCFC field trial units, with selling prices of about \$3000 kW^{-1} expected when its manufacturing capability of 50 MW $year^{-1}$ was reached in late 2001 or 2002. These high capital costs restrict the cost-effective application of fuel cell technology for stationary applications to locations where grid power is either unavailable or where extending distribution lines is expensive or unfeasible. As fuel cell system costs decline, however, new markets will become accessible. These market opportunities are discussed below.

3 CURRENT STATUS OF FUEL CELL TECHNOLOGY FOR TRANSPORTATION APPLICATIONS

There has been a strong push to develop fuel cells for use in light-duty and heavy-duty vehicle propulsion since about the early 1990s. Most attention is focused on the use of PEMFCs for transportation applications, with the fuel cell systems running on either pure hydrogen or reformate from refinery products or methanol. This focus on PEMFC is mainly due to their low temperature operation and their capability for intermittent operation, but efforts are also under way to develop DMFCs and AFCs for vehicle applications, as well as SOFC auxiliary power units (APUs).

Great strides have been made in increasing the power density of PEMFC systems, and this has significantly improved the practicality of using PEMFCs as the primary power source for fuel cell electric vehicles (FCVs). The progress of two of the leading companies in developing PEMFCs for vehicles, Ballard Power Systems and General Motors, demonstrates the great achievements that have been made. In 1989, Ballard's PEMFC stacks achieved just 100 $W\,l^{-1}$ of power density. By 1996, just 7 years later, over 1100 $W\,l^{-1}$ were achieved, representing greater than an order of magnitude improvement.[4] Ballard's current PEMFC stack technology for transportation applications, the Ballard Mark 900 series of fuel cells, is designed for high-volume manufacturing. The Mark 902, unveiled in late 2001, achieves a remarkable 2200 $W\,l^{-1}$ of power density.[5]

Similarly, General Motors has recently unveiled two new generations of PEMFC stack technology that show remarkable progress. First, the "Stack 2000" is a 200 cell design that has been incorporated into General Motors' HydroGen1 and Chevy S-10 FCV prototypes, and has demonstrated a power density of 1600 $W\,l^{-1}$ in a 94 kW (continuous) fuel cell stack.[6] In the Chevy S-10 pickup truck prototype, the Stack 2000 is coupled with General Motors' Gen II gasoline fuel processor, that converts "clean" gasoline into a hydrogen rich gas stream for the fuel cell system (General Motors, 2001). Second, General Motors has recently announced an even more advanced stack design that is reported to pack 1750 $W\,l^{-1}$ into a 640 cell design that is rated at 102 kW continuous and 173 kW peak.[7]

A cutaway drawing of the prototype DaimlerChrysler NECAR 4 that employs PEMFC technology from Ballard, shown in Figure 1,[8] illustrates how modern fuel cell systems can now be packaged into small light-duty vehicles. This Mercedes A-Class vehicle uses a liquid hydrogen storage tank and a 55 kW electric drivetrain. Another NECAR 4 design uses a compressed gas hydrogen tank, and the NECAR 5 design runs on methanol that is reformed into hydrogen on board the vehicle.

However, despite these great improvements in automotive PEM fuel cell system power density, significant challenges remain for the commercialization of FCVs. Two recent studies have helped to identify the remaining challenges.[9, 10] These challenges include:

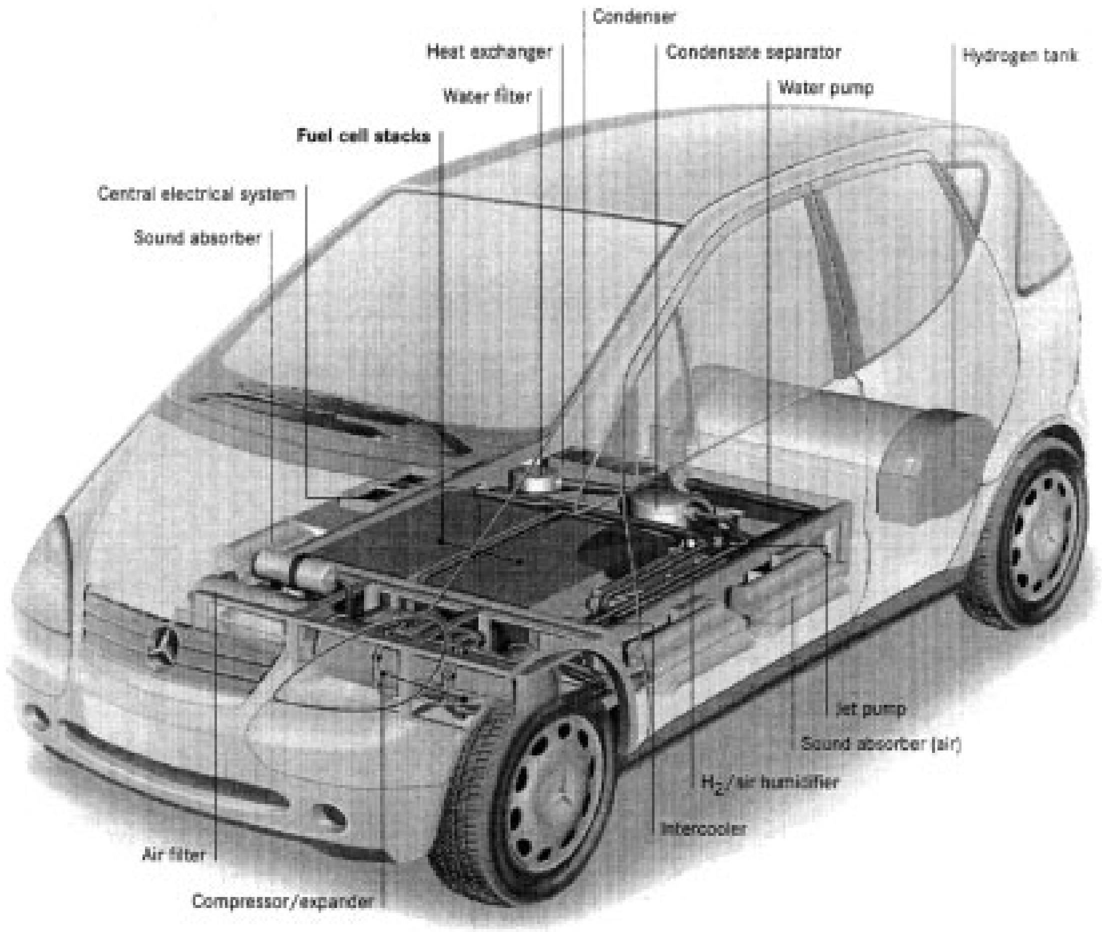

Figure 1. The DaimlerChrysler NECAR 4 DHFCV. (Figure from DaimlerChrysler AG; DaimlerChrysler, Corporate Communications, Stuttgart (Germany), Auburn Hills, (MI/USA), 03/99.)

- the difficulty and expense of developing a hydrogen refueling infrastructure for direct-hydrogen FCVs;
- the development of compact and low cost fuel reformers for liquid hydrocarbon fueled FCVs;
- the need for onboard storage systems for hydrogen that are simultaneously safe, compact, lightweight, inexpensive, and quick to refuel;
- cost reductions in fuel cell stacks, auxiliaries, electric motors, inverters, and peak-power batteries or ultracapacitors; and
- lack of strong market drivers and transportation energy policies for FCVs.

These remaining difficulties for FCV commercialization are significant, but considerable efforts are being made to address them by automakers, energy companies, government research labs and agencies, and academic institutions. We believe that the chances are good that the efforts being made to bring FCVs to market will ultimately be successful, but these remaining challenges make the timing of the introduction of mass-market FCVs uncertain at this time.

In addition to light-duty passenger vehicles, other transportation applications of fuel cell technology that are being explored include urban buses, heavy-duty truck APUs, delivery vehicles, forklifts, airport baggage handling vehicles, mining vehicles, golf carts, scooters, boats, and even airplanes. Of these, the urban bus market segment has received the most attention, with fuel cell bus demonstration projects being conducted by Ballard Power Systems and the US Department of Energy (DOE) in conjunction with Georgetown University. Two generations of buses have been built at Georgetown, with the first one using an IFC PAFC system and the second using an Xcellsis PEMFC system, and both employing hybrid-electric drivetrains. A third generation bus is planned that will use a nonhybridized PEMFC system. Ballard/Xcellsis PEMFC "Zebus" buses have successfully operated in Vancouver, Chicago, and Sacramento, with the first trials starting in 1998, and DaimlerChrysler has produced the earlier NEBUS and recent Citaro fuel cell bus that also employ Ballard fuel cells. The NEBUS and the Citaro are both fueled by eight compressed hydrogen gas tanks that are carried on the roof over the front axle. However, the 250 kW fuel cell system, which in the NEBUS was in the back where the diesel engine is typically located in conventional buses, is on the roof in the center of the Citaro. Commercialization plans for the Citaro and Zebus fuel cell buses are discussed below.

One interesting consideration for fuel cell systems developed for transportation applications is the possibility of "hybridizing" the fuel cell system with batteries or other energy storage system to provide a given amount of power with a smaller fuel cell stack. The use of batteries or capacitors would enable the recapture of braking energy through regenerative braking, and it could lead to a more cost-effective design (particularly in the near term) due to high fuel cell stack costs, but it would also involve additional system complexity. Furthermore, for reformer-based vehicles, hybridization of the fuel cell power system with batteries is one approach to alleviating the problem of slow reformer transient response. Of the recent fuel cell concept vehicles, DaimlerChrysler's NECAR line and the Ford P2000 are not hybridized, while Toyota's two vehicles, the DaimlerChrysler Natrium, the Renault/Volvo vehicle, the fuel cell version of the GM EV1, Nissan's prototype, and VW's prototype all use batteries, and the Honda FCX-V3 and Mazda's vehicle use ultracapacitors.

4 UNIQUE ATTRIBUTES OF FUEL CELL VEHICLES

Fuel cell vehicles have a somewhat unique set of requirements of fuel cell technology. First, automotive fuel cell systems must be more lightweight and compact (i.e., have high power densities by both mass and volume) than fuel cell systems used for stationary applications (from about 20 to 250 kW). Second, they must be tolerant to rapid cycling and on-road vibration, yet they must only operate reliably for 5000 h or so, while stationary systems must be able to operate for 40 000–50 000 h between major system overhauls. Third, fuel cell systems for vehicles must be able to respond rapidly to transient demands for power, unless they are "load-leveled" by hybridizing them with a battery or ultracapacitor power systems. Fuel cells for stationary systems may also be used for load-following with transient demand requirements, possibly with the aid of a peak power battery system, but they also will be used for steady baseload power or "net metered" to allow constant power operation if connected to the utility grid.

Given these requirements, hybrid and nonhybrid PEMFC systems are the leading contenders for automotive fuel cell power, with additional attention focusing on the DMFC version of the technology and the possibility of using SOFC systems as APUs for cars and trucks. All of these fuel cell systems, both as main vehicle power systems and as APUs, have the ability to support the new wave of vehicle electronics being introduced. New or planned electronic gadgetry on vehicles include navigation systems, extensive onboard communications, voice-activated controls, exterior alternating current (a.c.) power supplies, computer controlled power-assisted active suspension, collision-avoidance systems, electric A/C compressors, "drive-by-wire" steering, side and rear-view bumper cameras, electronic tire pressure control, and generally greater computer power for increasing control of various vehicle systems. The need for these systems has already led to a new 42 V standard for vehicle auxiliaries in order to deliver more power, and electric vehicles and APUs provide an efficient way to meet these power demands.

More generally, FCVs are considered attractive potential replacements for internal combustion engine vehicles because they can offer similar performance to conventional vehicles along with several advantages. These advantages include better environmental performance, quiet (but not silent) operation, rapid acceleration from a standstill due to the torque characteristics of electric motors, and potentially low maintenance requirements. Furthermore, FCVs have the potential to perform functions for which conventional vehicles are poorly suited, such as providing remote electrical power (for construction sites, recreational uses, etc.) and possibly even acting as distributed electricity generators when parked at homes and offices and connected to a supplemental fuel supply. Figure 2 presents the results of one analysis of the full fuel-cycle air pollutant emissions of hydrogen FCVs compared with conventional and hybrid vehicles, and shows that FCVs running directly on hydrogen can provide great potential air quality benefits.

One important feature of FCVs that remains crucial for their development is the fact that PEM fuel cells run on

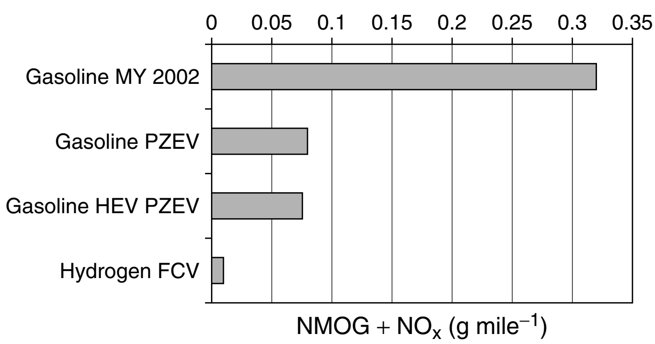

Figure 2. Fuel-cycle air pollutant impacts of hydrogen FCVs and gasoline powered alternatives. *Source:* [9] Notes: FC, fuel cell; HEV, hybrid electric vehicle; NMOG, nonmethane organic gases; NO_x, oxides of nitrogen; MY, model year; PZEV, partial zero-emission vehicle credit vehicle.

either pure hydrogen or a dilute hydrogen gas "reformate" stream (ignoring for a moment the prospects for direct methanol fuel cells that are still in an early stage of development). This hydrogen can either be stored onboard the vehicle in one of several ways, or it can be generated from another fuel with an onboard reformer. Onboard reformation introduces significant cost and complexity to FCVs, and also tends to diminish their energy efficiency and environmental benefits. For these reasons, most automakers agree that storing hydrogen onboard FCVs is the best ultimate solution, but no hydrogen storage system has yet been developed that is simultaneously lightweight, compact, inexpensive, and safe. Further advances in hydrogen storage, so that FCVs can refuel quickly and have driving ranges comparable to conventional vehicles, is thus a key area for further development. Prototype FCVs have been built that store hydrogen as a cryogenic liquid, as a compressed gas, in metal hydrides, and as sodium borohydrate, and other vehicles have been demonstrated with reformers for methanol and reformulated gasoline.

5 INNOVATION AND MARKETING OF NEW PRODUCTS

Fuel cells, like all nascent technologies, are characterized by high manufacturing costs, uncertain long-term performance and durability, and lack of a clear technological consensus or "dominant design" for the individual niches for which they are being considered. As commercialization of fuel cell technology proceeds, manufacturing volumes will increase, costs will fall, and long-term product performance and durability will be better understood. However, fuel cell systems will not easily or "automatically" penetrate stationary and automotive power markets, despite their attractive qualities. This is due not only to uncertain durability of fuel cells and potential cost differences between fuel cell systems and competing systems, but also because the incumbent technologies are typically "locked in" and have a series of network relationships that reinforce their continued use.[11] For example, fuel cells for stationary applications fit into the emerging field of distributed generation (DG), but all DG technologies face difficulties in fitting into established electrical power systems that have been designed around large-scale centralized power production and a complex network of electricity transmission and distribution infrastructure. Many regulatory and technical steps are needed for fuel cells and other DG technologies to safely interconnect to utility grids, and each of these represents a potential obstacle, particularly in the context of electricity industry restructuring and the uncertainty that this imposes on the industry.

In the transportation area, the barriers are perhaps even more onerous, with a motor vehicle system in place that has evolved for over a century to support gasoline-powered, internal combustion engine vehicles. In most places of the world, the vehicle-refueling infrastructure and vehicle service industries that support the use of motor vehicles are entrenched in a way that will make change away from the status quo inevitably difficult. Furthermore, due to environmental pressures and partly in response to progress in fuel cell development, other options for reducing fuel consumption and emissions from motor vehicles are also under intense development; they are a "moving target". Such options as hybrid-electric vehicles, with a small gasoline or diesel engine coupled with a battery-powered electric driveline, are capable of achieving impressive levels of efficiency and environmental performance at cost levels that FCVs will be challenged to meet.

Thus, a key aspect of the early commercialization of fuel cell systems is to find niches in which they have competitive advantages, and to exploit these niches in order to build production volume, lower costs, and ultimately reach other market niches, which in turn will lead to even greater production volumes and lower costs. This process has come to be known as the "virtuous cycle", and almost all successful technologies have benefited from it. A key aspect of the virtuous cycle is the cost reduction that occurs through a combination of scale economies in production, and also learning that takes place with regard to both product and manufacturing process design.

The concept of the "learning curve" or "experience curve" captures this phenomenon, whereby manufacturing cost histories of many different products have shown a consistent pattern of cost reduction with increases in cumulative production volume. In essence, manufactured products tend to decline in cost by 10–30% with each doubling of *cumulative* production volume (see Ref. [12] for review of the literature and application to automotive fuel cell technology). This logarithmic effect means that cost reductions are achieved rapidly early in a product's history, when doublings in cumulative production occur relatively quickly, and then slow down as the doublings take longer to achieve. Thus, if a product can gain an initial foothold in the market due to some competitive advantage, this can trigger the virtuous cycle and ultimately allow a new technology to break into a market that is dominated by an incumbent technology.

Thus, it is imperative that fuel cell systems for stationary and transportation applications find initial niches where they are attractive, even if these niches are relatively small. For stationary systems, this might include the market for "premium power" where certain uses require electricity reliability that is much greater than that of grid power. Onsite fuel cell systems should be able to generate power with a high degree of reliability, particularly if combined with backup systems, and this provides the type of competitive advantage that could give them a foothold in the market from which they can expand. In the transportation sector, the desire to achieve zero tailpipe emissions for vehicles that operate in dense urban areas is a driver that could give FCVs an important niche. The only zero-emission vehicle type other than direct-hydrogen FCVs that is practical at the present time is the battery EV, and this vehicle type is characterized by short driving ranges, long recharge times, and potentially high lifecycle costs. To the extent that zero-emission vehicles are encouraged or even mandated in certain areas, direct-hydrogen FCVs may have to compete only with battery EVs and not the entire suite of vehicle technology options. This could give them a much firmer foothold to break into motor vehicle markets.

6 CURRENT STATIONARY SYSTEM COMMERCIALIZATION PLANS

Demand for stationary fuel cell systems is expected to grow sharply over the next decade, and several companies are planning commercial products to enter this market. Allied Business Intelligence has forecast that 15 GW of fuel cell systems are expected to be in operation around the globe by 2011, compared with just 75 MW in 2001.[13] Meanwhile, the State of California has recently announced the formation of a stationary fuel cell collaborative program that seeks to install 20 MW of fuel cell systems in California by the end of 2002, with additional goals of having 100 MW of fuel cell generation by 2003 and 500 MW of fuel cell generation by 2004.[14] This demand for fuel cell power fits into the overall context of the expected burgeoning growth of DG, which is expected to be a 20 GW year^{-1} market on a global basis.[15]

At present, the 200 kW PAFC units manufactured by IFC are the only commercially available stationary fuel cell systems on the market. However, a host of other companies have plans for products for the stationary market. These include Ballard Generating Systems, Plug Power, IdaTech, and Avista Labs for PEMFCs in residential and commercial buildings; Nuvera Fuel Cells for PEMFCs in remote telecommunication and UPS applications; Siemens Westinghouse, Honeywell, and Ceramic Fuel Cells for SOFCs in DG; and Fuel Cell Energy for larger-scale (300 kW–3 MW) MCFCs in DG. Meanwhile, other companies are focusing on somewhat more specialized niches, such as Proton Energy Systems and Hydrogenics, with PEMFC systems coupled to renewable hydrogen production via electrolysis; and H-Power with a focus on remote telecommunications (as well as niche transportation applications). While the details of these companies' commercialization plans are largely proprietary, to the extent that they have been made public they tend to reveal an initial focus on regions with high electricity costs, market niches with needs for high reliability "premium power", areas where grid congestion is a problem, and areas where "opportunity fuel" such as landfill gas is available. The commercialization plans of these companies are thus for initial products that fit into niches where fuel cell power is particularly advantageous, presumably with the hope that broader markets will open up as manufacturing costs fall.

Several companies are focusing on PEMFCs for stationary power generation, but the development of SOFC systems has been given a recent boost by DOE. The Solid-State Energy Conversion Alliance (SECA) has recently awarded contracts totaling $500 million to four different teams, in the hope of accelerating the development of SOFCs. These teams include those led by Honeywell, Siemens Westinghouse, Delphi and Battelle, and Cummins Power Generation and McDermott Technology.[16] DOE has a near term manufacturing cost goal of $800 kW^{-1} for SOFC stacks, with $400 kW^{-1} as a longer term goal.[16]

7 CURRENT VEHICLE COMMERCIALIZATION PLANS

FCVs are still in the research, development, and demonstration phase, and all major automakers have substantial development programs underway. The FCVs closest to commercialization are buses. Fuel cell buses are now being demonstrated in Vancouver, Chicago, Sacramento, Palm Desert, and Washington, DC, and light-duty FCV test programs are underway in Sacramento (under the California Fuel Cell Partnership), Germany, England and Japan. In a recent development, Ballard Power Systems and Xcellsis, Inc. have announced that they will deliver 30 fuel cell powered "Zebuses" to European customers beginning in 2002. These buses will employ the latest Ballard fuel cell technology, the Mark 902 system.[17]

The exact commercialization plans for FCVs have not been disclosed by automakers, but they have suggested initial plans for introducing these vehicles. Table 1 lists the prototype vehicles that have been unveiled to date, along with the latest public statements by each company about their plans for commercialization. In general, introduction of FCVs into limited fleet applications is expected in the 2003–2005 timeframe – in the hundreds and perhaps thousands, with broader introduction to private consumers expected in about 2008–2010.

In general, automakers agree that hydrogen is the ultimate fuel for FCVs, and that FCVs in the future are

Table 1. Recent FCV prototypes and commercialization status for major automakers.[a]

Manufacturers	Recent prototype vehicles	Fuel cell system	Commercialization timeframe
BMW	H_2 ICE 12-V 750 hL	PEM APU and Delphi SOFC APU (CHF powered)	Fuel cell APU introduction ca. 2006
Daihatsu	MOVE FCV-K-II	Toyota Direct-H_2 (hybrid)	Unknown
DaimlerChrysler	NECAR IV FCV; NECAR V FCV; Natrium FCV; Citaro FC Bus; DMFC Go-Cart	Ballard Direct-H_2; Ballard MeOH; Ballard Direct-H_2; Ballard Direct-H_2; Ballard DMFC	Limited introduction in 2004
Fiat	Seicento Elettra H_2 FCV	Nuvera Direct-H_2	Unknown
Ford	Th!nk Focus FCV; P2000 FCV	Ballard Direct-H_2; Ballard Direct-H_2	Limited introduction in 2004
General Motors	HydroGenI Opel Zafira FCV; Chevy S-10 FCV	GM Stack 2000; GM Stack 2000 CHF	Availability in 2005, volume production in 2008–2010, goal to be first company to sell 1 million FCVs
Honda	FCX-V3 FCV	Ballard Direct-H_2	Introduction in 2003 of less than a few hundred direct-H_2 FCVs
Hyundai	Santa Fe FCV	International Fuel Cells Direct-H_2	Unknown
Mazda	Premacy FC-EV	Ballard MeOH	Participation in programs with Ford Motor Group and Th!nk
Mitsubishi	MFCV Concept Vehicle	Mitsubishi MeOH	Working with Mitsubishi Heavy Industries to develop commercial FCV by 2005
Nissan	R'nessa SUV; Xterra SUV	Ballard MeOH; Ballard MeOH	Limited introduction in 2003 or 2004, working with Renault to develop commercial FC technology by 2005
Peugeot/Citroen			Working with Renault to develop commercially viable FCV by 2010
Renault	FEVER FCV	Direct-H_2	Working with Peugeot/Citroen and Nissan to develop commercially viable FCV by 2010
Toyota	FCHV-4 FCV; FCHV-5 FCV; FCHV-BUS 1	Toyota Direct-H_2; Toyota CHF (hybrid); Toyota Direct-H_2	Limited introduction in 2003, expect full commercialization ca. 2010
Volkswagen	Bora HYMotion FCV	Direct- H_2	Working with Volvo on MeOH fueled hybrid FCV
Volvo			Working with Volkswagen on MeOH fueled hybrid FCV

[a]*Source:* company press releases. Notes: APU, auxiliary power unit; CHF, clean hydrocarbon fuel reformate; DMFC, direct methanol fuel cell; ICE, internal combustion engine; MeOH, methanol reformate; SOFC, solid oxide fuel cell.

likely to operate directly on hydrogen. But there are significant differences of opinion with regard to the evolution of vehicles and refueling systems in the meantime. As of late 2001, General Motors, Toyota, Nissan, Renault and Hyundai favor hydrocarbon-based FCVs, using gasoline-like fuels, citing the fact that an infrastructure for petroleum fuel distribution is already in place. DaimlerChrysler supports methanol fuel cells (along with other options), believing that it is easier to convert methanol to hydrogen than to convert gasoline, while using a similar distribution system. Meanwhile, Ford and Honda are focusing on direct-hydrogen FCV designs that avoid onboard conversion from other fuel types, but require a hydrogen-fueling infrastructure.

Another potential early application of fuel cells is APUs for long-haul, heavy-duty trucks.[18] In the US, these trucks idle up to 10 h each day, and as much as 50% of total engine run time. Idling consumes significant amounts of diesel fuel, accelerates wear and tear on the engine, and generates large amounts of noise, vibration and air pollution. The total cost of idling heavy-duty trucks in the US is over a billion dollars per year for fuel and extra maintenance.[19] An attractive APU that could replace the main engine is a diesel-fueled fuel cell. Two types of fuel cells could run on diesel fuel: proton-exchange membrane fuel cells of the type being developed for cars, with a device to convert the diesel fuel to hydrogen, or solid-oxide fuel cells that can operate directly on diesel fuel. Recreational vehicles, widely used in the US for overnight travel, are another potential fuel cell APU market; they spend a large amount of time in ecologically-sensitive national parks and other wilderness locations.

No companies have announced plans to commercialize fuel cell APUs, in trucks or any other vehicles, but BMW has made various announcements regarding the development of fuel cell APUs and applications in passenger cars.[20] Freightliner and Cummins have participated in fuel cell APU development projects in heavy duty diesel trucks, but future plans have not been announced to date.

The use of fuel cells as APUs in long-haul trucks might lead to a migration of these clean, efficient devices to other trucks (and even cars), and also accelerate electrification of the truck's drivetrain, steering, braking and other accessories, leading to even further efficiency and environmental benefits. An analogy may be computers in cars, which initially were used to control emissions, but soon gained much wider applications.

In addition to conventional cars, trucks, and buses, additional transportation applications of fuel cell technology include scooters, "neighborhood" EVs and golf carts, forklifts, mining vehicles, airport baggage handling vehicles, airplanes, boats and even submarines. Commercialization plans for these vehicle types have not been made public in detail, but a few companies are clearly focusing on these markets. For example, Asia Pacific Fuel Cell Technologies hopes to work with a Taiwanese scooter developer to produce fuel cell scooters for the Asian market, and several companies are experimenting with fuel cell powered golf carts and neighborhood EVs.

Fuel cell airplane designs have been developed by Aerovironment, which is testing the Helios high-altitude, unmanned, solar-powered aircraft. This plane soared to a record altitude of over 29 300 m (96 500 feet) (for a non-rocket powered aircraft) after being launched from Kauai, Hawaii in August 2001. The plane achieved a speed of $275\,\mathrm{km\,h^{-1}}$, or Mach 0.25, operating only on solar power. Battery systems were used for initial tests of the Helios, but ultimately a fuel cell/electrolyzer system will be used, and the plane will then be able to fly for extended periods of time. Also, a small single-engine aircraft that is ultimately planned to operate with fuel cell power is being developed by Advanced Technology Products, Inc. The first version of the aircraft will operate using lithium-ion batteries, but subsequent generations are planned that will use batteries augmented with a 12 kW PEMFC system, and subsequently with a 25–75 kW PEMFC.[21]

With regard to marine applications, IFC has produced a 30 kW PEMFC unit for the Navy's Lockheed Deep Quest vehicle. This submarine vehicle can operate at depths of up to 1500 m. Meanwhile, Ballard Power Systems has produced an 80 kW PEMFC fuel cell unit for submarine use that is methanol fueled.[1] And, a German consortium led by STN ATLAS Elektronik GmbH, with four other companies and three research institutions, has developed the "DeepC" prototype fuel cell-powered, unmanned, underwater vehicle that is capable of traveling to depths of 4000 m. The consortium hopes to commercialize the vehicle in 2004 for oceanographic research and other undersea explorations.[22]

8 SUMMARY AND CONCLUSIONS

Fuel cells have unique attributes that are attractive to automotive and electricity consumers, and also to automotive and electricity companies. These unique attributes are highly valued in certain market niches and segments. As costs come down and products are enhanced, companies and governments will realign their polices and business strategies to accommodate fuel cell attributes and opportunities.

One can envision various scenarios and pathways by which fuel cells expand their presence. Shell International, well known for its sophisticated scenario planning, posits two energy scenarios for 2050.[23] One of them is centered around and motivated by fuel cell advances. In this scenario, fuel cell sales start with stationary applications for businesses willing to pay a premium for highly reliable power without voltage fluctuations or outages. They then spread to vehicles. By 2025, in this scenario, half of all vehicle sales in OECD countries and one quarter of all vehicle sales worldwide are fuel cell vehicles. Under this fuel cell "success story" scenario, fuel cells could eventually become the dominant energy conversion devices across all sectors, fueled by hydrogen in some settings and directly with natural gas or landfill gas (with high temperature fuel cells) or methanol (with direct-methanol fuel cells) in others.

There are no obvious barriers to fuel cells' entry into the marketplace, and there are good reasons they will be attractive and prove to be a superior product. Their high efficiency, low emissions, ability to accommodate diverse fuels, high quality of generated electricity and their exceptional suitability to hydrogen are strong factors in their favor. Three trends serve to reinforce the attractiveness of fuel cells: motor vehicles transitioning from mechanical and hydraulic systems to electrification, electricity generating moving toward distributed generation, and continuing international commitments to reduce greenhouse gas emissions and the environmental footprint of industrial products.

However, despite great improvements in fuel cell power density over the past decade, and demonstration of promising performance, both stationary and automotive fuel cell systems face critical remaining challenges. These include primarily cost reduction, where costs on the order of \$500–800 kW^{-1}-peak are required for competitive stationary systems, and costs on the order of \$50–100 kW^{-1}-peak are required for competitive FCVs. These cost levels are far below current cost levels for various fuel cell technologies that are in prototype and low volume production. Additional challenges include fuel cell system durability, where development goals are for 40 000–50 000 h between major overhauls for stationary systems and 4000–5000 h for automotive systems, development of efficient and low cost fuel reformers, and development of hydrogen storage systems for vehicles that are inexpensive, lightweight, compact, safe and quick to refuel.

In the end, the future is highly uncertain. We remain optimistic, particularly with regard to the use of fuel cells in niche applications where they offer clear advantages over other options. But when or whether fuel cells flourish remains unknowable. It is entirely plausible, for instance, that vehicles will follow a more incremental path from today's internal combustion engine (ICE) systems to hybrid electric cars that rely on small combustion engines hybridized with electric-drive technologies. And it may be that continuing refinements of these hybrid technologies will keep fuel cells at the margin, competitive only in specialized niches. Stationary fuel cells for distributed generation may face greater than expected difficulties due to durability problems or issues with integration into existing electrical grids. What is certain is that, at a minimum, fuel cells will be an important technology alternative that receives increasing attention and R&D resources for some time.

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