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A Preliminary Assessment

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ABSTRACT

In 1997-98, most of the major automotive companies announced plans to sell 100,000 or more fuel cell vehicles each by 2005. Those plans are being stymied by the daunting challenge of developing and commercializing an entirely new propulsion system, possibly operating on a new fuel. A new approach is needed that targets market niches where the advantages of fuel cells can be exploited and their disadvantages downplayed. This paper explores the potential use of fuel cells in auxiliary power units (APUs) on-board various types of cars and trucks – in luxury passenger vehicles, law enforcement vehicles, contractor trucks, specialized utility trucks, recreational vehicles, refrigerated trucks, and line-haul heavy-duty trucks. We analyze power requirements, volume and weight targets, costs, market sizes, and potential benefits for several fuel cell technologies and fuels. The attributes of market applications are matched with fuel cell attributes to assess the market potential of fuel cell APUs. Although data are insufficient and more analysis is needed, we find that several market applications could play key roles in introducing fuel cell technologies to the transportation sector.

INTRODUCTION

Fuel cells are increasingly touted as the dominant automotive propulsion technology of the future (*1*). Almost every international automotive company has launched major fuel cell vehicle development programs, and the Bush Administration has designated fuel cells vehicles as central to federal automotive R&D efforts (*2*). However, it is becoming apparent that the high initial costs of fuel cells preclude their introduction to the mass market for some time. A new approach is needed that focuses on niche markets. One such market is auxiliary power units (APUs). Fuel cells as APUs offer potential advantages in overall energy efficiency, emissions, and costs.

For each particular APU application, fuel cells have a unique set of requirements and characteristics. We examine these requirements and characteristics for a set of promising market applications, though this assessment is limited by data availability.

MARKET CHARACTERIZATION

The list of APU R&D initiatives and demonstrations in Table 1 (*3,4,5,6,7,8,9*) is suggestive of the broad range of APU applications. Markets for automotive APUs are likely to include applications where the vehicle engine is currently operated inefficiently in order to provide accessory power (e.g. heavy-duty truck idling) or where non-propulsion diesel engines are currently run to supply power (e.g. refrigeration units). Many heavy-duty vehicles idle regularly to power the cabin's climate control and electric accessories, and some passenger vehicles, such as law enforcement vehicles, also idle for long durations to power lights and communications systems. Other vehicles that operate tools and machinery may idle their engines for extended periods. In Table 2, we list a range of potential fuel cell APU market and technology applications.

APU Applications

Key parameters in determining where and how fuel cell APUs might be attractive include operational characteristics of the auxiliary power (total power requirement, time of use, etc.) and market variables (total vehicle cost, sales, and trends). Below is an assessment of potential market applications, developed from a review of the literature, interviews with industry experts, and analysis of available data.

1. Luxury Passenger Vehicles

The electrical load on modern cars continues to increase. New accessories and power demands include on-board communication systems (e.g., navigation information, internet connections), heated seats, additional entertainment devices (DVD, television), and continuing conversion of mechanical and hydraulic subsystems to ("by-wire") electric control, as well as the usual draws for heating and cooling. Increasing at about 6% per year, the on-board electric power demand for light duty vehicles is approximately 2 kW, with continuing increases expected into the foreseeable future (*10*). The cost for computer and electronic controls in today's luxury car is about $2,000, or less than 5% of the entire vehicle cost, and is projected to increase to 40% of the vehicle cost in a decade (*10*). These increasing electric power demands have prompted the auto industry to explore a transition from 12/14-V systems to 36/42-V systems. Higher voltage decreases electric losses and allows for greater use of integrated starter/generator systems, more energy-intensive cabin devices (e.g., windshield heating), and increased electrification of vehicle systems for improved performance and/or efficiency (e.g., electric steering, braking) (*11*).

Typically, stock alternators on vehicles are rated between 50 and 90 amps of current, offering less than 2 kW of total power capability from the main engine. Table 3 (*13*), below, highlights the electric power demands of a more-electrified vehicle. Many of the accessories (e.g., active suspension) are not considered initial APU application possibilities because of their large but infrequent power demand. Eventually, more of the listed vehicle accessories are likely to be powered electrically (in hybrid gasoline-electric with added batteries or fuel cell APU-equipped vehicle systems) with 36/42-V electrical systems.

The increased electrification of vehicles could offer a niche market for small electricity-generating fuel cell units. If accessories and vehicle systems (pumps, fans, rear defroster, air conditioner, etc.) could be powered by another source, the engine could turn off when the vehicle is at rest without costly additions to battery capacity. "Engine off" operation could yield 20-25% fuel savings (*12*), or even as much as 30% (*13*). Due partially to the potential for absorbing cost increases, the most likely near-term markets for APU devices to reduce high parasitic accessory demands on engines are in high-end vehicle models, such as luxury sedans and sport utility vehicles (SUVs).

In determining the most appropriate APU size for near-term electrification of passenger cars, we calculate power demands for all accessories and amenities that might be required while the vehicle is at rest. Table 3 lists the maximum total power requirement for an APU in a luxury passenger car in winter and summer conditions. As indicated, the total maximum APU power could be as high as 5-7 kW. Further electrification of vehicles and the introduction of more amenities such as on-board refrigeration and multimedia capabilities (DVD, television, Internet) would require even more power.

Key performance and cost targets for automotive fuel cells were specified by the Partnership for a New Generation of Vehicles (PNGV), and later modified in 2002 by the subsequent FreedomCAR program (*14*). Because these targets were developed for traction fuel cells, they can be used only for rough guidance. The FreedomCAR cost target is $45/kW. BMW, with a major fuel cell APU program, states that this cost target could be ten times greater for APU applications and still be competitive (*3*). Other targets (for the main-propulsion fuel cell system) are a power-volume ratio of 220 W/liter and a power-mass ratio of 325 W/kg (including the fuel processor, stack, and auxiliaries, and excluding the fuel tank and DC-DC converter). Again, BMW and its partner, Delphi, propose less aggressive targets for APU systems: 50 – 100 W/liter and 50 – 100 W/kg, for a 3–10 kW gasoline reforming system (*15*).

Due to the size of fuel cells, it may be that SUVs will prove more attractive initially for fuel cell APUs than do luxury cars. It will be difficult to place fuel cells and their fuel supply in tightly packaged cars, especially for initial generations of fuel cell technology. Both luxury car and SUV markets are significant. Luxury cars comprised about 9% of the total U.S. vehicle sales in 2001, or about 1.2 million cars (*16*), and have been increasing steadily over the years. But the SUV population has also been increasing rapidly in the U.S. – achieving 21% of the 2000 light duty market (*17*)), with luxury SUVs accounting for about 2% of sales, about 300 thousand sales per year (*16*).

2. Law Enforcement Vehicles

As with passenger cars, on-board computer equipment and other power draws are increasing in police cars. Police cars may be an attractive early market because of their frequent idling, and increased need for larger accessory power draws (e.g., radio communication, roof lights, sirens, etc.). Typically, law enforcement vehicles are standard car and SUV models converted for use by police departments and highway patrol departments. Aside from the addition of radios, lights, and sirens, the new vehicles are commonly "upfitted" with alternators with higher electrical power capability. Stock alternators with approximately 75 amps of capacity are typically replaced with alternators with 200-amp maximum current that generate 120 amps (~1.5 kW at 12 VDC) at vehicle idle. Chevrolet's new Impala offers a higher performance 96-amp alternator option in an effort to avoid the need for aftermarket electrical "upfitting" of law enforcement vehicles (*18*). Similarly, an option on Dodge Intrepids offers higher current alternators to accommodate police fleets. An APU for this application would require 1.5 kW for vehicle idling situations and up to 2.5 kW for maximum current draw (including sirens, lights, and radio).

Police vehicles are particularly attractive because they often are centrally refueled and maintained by the fleet operator, mitigating fuel supply problems. A 1998 survey revealed that as many as 28% of law enforcement fleets planned to acquire alternative fuel vehicles for the following year, with the vehicles being predominantly fueled by compressed natural gas (*19*).

Another attraction of police vehicles is the reduced need for cargo volume (and thus more space for fuel tanks). A fleet trade organization survey revealed that in 1998, 10% of police vehicle purchases were light- or medium-duty trucks and 85% were cars (*19*). Total law enforcement sedan purchases in the U.S. are between 60,000 and 70,000 per year (*20*).

3. Contractor Truck/Pick-up

Dodge and General Motors (GM) have unveiled plans to sell hybrid-electric pick-up trucks, beginning in in 2004 and 2005. The Dodge Ram is to generate up to 20 kW of electricity running off the main engine. In addition to acting as a stationary generator, the vehicle is expected to have a net overall fuel economy improvement of 15%. This hybrid-electric vehicle market was described by DaimlerChrysler Vice President Bernard Robertson as an option for outdoor enthusiasts, farmers, contractors at remote work sites, and homeowners desiring back-up power (*21*).

Similar to the Dodge, GM claims 10-15% fuel economy savings for their hybrid-electric truck, while generating up to 4.8 kW of electricity with high voltage alternating current (AC) outlets. The GM full-size pick-ups purport to integrate a 42-V battery pack, electric power steering, regenerative braking, and automatic engine shut-off during stops (*22*). Although these planned work vehicles are pick-up trucks, they could just as easily be SUVs and vans.

A fuel cell APU-equipped, light-duty truck could offer the same capability, only more so. With a fuel cell APU, the light truck could power a mobile office (with laptop computers, phones, etc.) as well as tools (drills and other power tools) for convenience in remote locations and construction sites. Vehicles commonly used in construction, landscaping, plumbing, and carpentry trades, due to remote work locations and power tool usage, could presumably benefit greatly from such APUs.

Although Dodge's truck is not yet market-tested, its projected specifications provide a benchmark for APU applications with similar services. The Dodge Contractor Special is expected to cost $5,000 more and weigh 250-300 lb more than the typical Ram (*22*). With output of 20 kW, a fuel cell targeted for this particular application would need to provide at least 70 W/lb (150 W/kg) at a cost no more than $250/kW to be competitive with the Ram prototype. Dodge expects total sales of this vehicle option to be 15 - 20% of Ram sales, or about 76,000 pick-ups annually (*23*). If the market for this accessory were 15% of all full-size pick-up trucks, the total annual U.S. market would be approximately 300,000 units.

4. Specialized Utility Trucks

Specialized utility vehicles are used for a wide assortment of applications. Many of these vehicles utilize engine power for power-take-off (PTO) devices. These non-propulsion devices include garbage crushers, cement mixers, lifts for power/telephone lines, and moveable platforms. Generally these devices are run from a hydraulic fluid that is compressed by the main engine. The fluid can have flow rates from 2-40 gallons per minute, at pressures up to 3000 psi. Companies that build power-take-off devices indicated to us that the approximate power required for these devices varies widely. Cement mixers and digger derricks could require 60 – 75 kW of power, garbage crushers 20 – 70 kW, and platforms and manlifts 5 – 35 kW.

The end uses and consumers of these devices are diverse, including utility (power, telephone, etc.) companies, municipal agencies, state highway departments, and university maintenance crews. This widely dispersed market with widely varying uses and demands is not easily simplified into generalizable auxiliary power characteristics.

Total sales of these vehicles were estimated with the U.S. Department of Commerce's *Vehicle Inventory & Use Survey*. The categories used in that survey are broader and do not match perfectly with the applications indicated above, but the survey provides some quantitative estimates of the potential markets. The survey suggests that about 70,000 new trucks were registered in 1997 that were classified as public utility, service, dump, tank, concrete mixer, and platform (with devices) trucks, which are the likely candidates for power-take-off devices (*24*).

5. Recreational Vehicles

Recreational vehicles come in many shapes and sizes (*25*) and often have many power requirements (heating and electrical appliances) on-board. Commonly these vehicles use electricity from hook-ups and diesel or liquefied petroleum gas (LPG, often referred to as propane) for power in remote locations where electric hook-ups are unavailable. In addition, furnaces for cabin heating and water heaters are commonly run directly on LPG. Therefore, most of the larger RVs have both LPG and diesel fuel tanks on-board.

One RV manufacturer discloses a typical list of on-board accessories (*26*). From this list, we estimate the maximum same-time power load is about 2 -3 kW (*26*). Recreational vehicle electricity "hook-ups" are widely available throughout the country at state and private campgrounds and are more convenient for powering on-board accessories than is propane. A representative from Kampgrounds of America (KOA), a nationwide RV service provider, indicated to us that typical campground electricity outlets allow 30 amps of current, while a higher current option of 50 amps is offered but rarely needed. These currents, at 120 VAC, equate to 3.6 and 6 kW of power availability to RV hook-ups, respectively. This information from KOA, along with that from a "typically" outfitted Winnebago RV (*25*), indicates that the probable electrical power requirement for most RV applications is 2 – 4 kW. However, some use more power, as suggested by the availability of 50-amp (6-kW) outlets and the availability of Winnebago RVs with installed diesel generators (2.8 to 7.5 kW). The auxiliary power use is almost entirely while an RV is at rest, where the RV generally plugs in to campground power supply. The attractions of diesel (and propane) generators are limited by the relatively few hours they operate, and usage restrictions in some RV parks due to their noise.

Not all RVs are candidates for an auxiliary power source. Smaller, towed RVs are presumed to have fewer accessories and lower power demand. Excluding those smaller RVs, about 190,000 RVs are sold each year that might be considered candidates for a fuel cell APU. These include RVs typically equipped with a generator – those classified as "motorized (types A, B, and C)," "towed 5th wheel trailers," and "travel trailers" (*27*).

6. Refrigeration units

Trailer refrigeration units (TRUs) are commonly installed on a wide range of trucks and trailers, including light and medium-duty beverage haulers (straight trucks) and heavy-duty refrigerated vans (semi-trailers vans). Some small- to mid-sized refrigerated vans (up to around 20 feet in length) may be equipped with cooling units that are primarily driven off the main engine. Some also have their own small electric back-up unit for when the main engine is turned off. The larger medium- and heavy-duty TRUs are entirely powered by their own separate engine-compressor systems with their own fuel tanks, independent of the main propulsion engine. Industry averages for heavy-duty TRUs include 2000 hours of operation per year with 0.6 – 1.1 gallons of diesel consumed per hour.

Unlike the truck engines, TRU engines are not idled. TRU engines are run in highly efficient operation ranges. Thus, the potential emissions and fuel saving from APU-powered TRUs is not as compelling as the truck idling case. Alternative power for TRUs is driven by environmental justice concerns. These units have been reported to run a disproportionate amount of time in socio-economically disadvantaged areas. Recent proposals by the California Air Resources Board to regulate these power units (*28*), TRUs have become candidates for low emitting, low noise APUs.

Discussions with a TRU manufacturer and a local TRU dealer helped us determine target parameters for potential fuel cell cooling applications. The US Department of Energy's

Technology Roadmap for 21st Century estimates the auxiliary power load of refrigeration units for larger trailer units can be up to 30 kW (*29*). Our contact with industry sources confirms that a 22 kW peak (with an average of about 10 kW) is adequate to drive the cooling systems for popular, representative full-size trailers. Targets for a fuel cell-driven TRU include an additional weight of about 70 kg, a 10 – 20 year operating life, and a $3,000 incremental cost for the fuel cell subsystem. Conventional TRUs cost roughly $20,000, weigh 500+ kg, and take up 1500 L. The two most common refrigeration trailer types are those for perishables (e.g. produce) and those for frozen foods (e.g. meat, ice cream). Perishable food trailers typically must have more closely managed temperatures, and are therefore runs near full-power for about 100% of the operation time. The frozen food trailer units, more frequently cycle on and off (10-30 times per day). These units may be operating near full-power for 50% of the time, and on stand-by (< 1 kW) for the other 50%.

The U.S. Department of Commerce reports that about 64,000 insulated refrigerated trailer units were sold in 2000 (*30*). Roughly 5% of these units have dual energy source capability. Along with the diesel-driven unit, these TRUs can plug into electric grid power (e.g., at loading docks).

7. Line-haul heavy-duty trucks

Of the APU applications discussed in this paper, the heavy-duty truck idling case is the best understood. The potential benefits of APUs in military, line-haul commercial freight carriers, and intermodal trucks include increased fuel efficiency, and reduced maintenance, emissions, and noise. Our previous work has addressed the large amount of avoidable idling by line-haul trucks. Stodolsky et al use a base case of 6 hours a day of idling, which equates to 1830 hours idled per truck per year (*31*). It is believed that about 400,000 trucks may fit this characterization (*31*). Substantial economic and environmental consequences result (*32*,*33*,*34*).

Drivers of Class 8 (heavy duty) trucks idle their main engines primarily to power climate control systems (heating and cooling in cabin) and electric accessories (televisions, lights, computers, etc.). Some alternatives, including small heating and air conditioning units and diesel-powered electricity generators, have been purchased for up to 5% of these trucks (*35*). The lack of widespread adoption of these alternatives is poorly understood but has been anecdotally attributed to high initial cost, loss of payload for trucks due to APU weight, system durability, and lack of awareness of the extent of idling repercussions.

A recent pilot survey of truck drivers revealed that likely in-cabin peak power demands for these trucks could total about 4-6 kW (*36*). As indicated in Table 4, we estimate that 3 kW may be adequate to supply the maximum same-time peak power for in-cabin accessory demand.

The design of commercially-available diesel-driven APUs provides some guidance in determining weight, volume, and cost targets for a prospective fuel cell APU. The U.S. Department of Energy's *Technology Roadmap for the 21st Century Truck Program* reports that typical (diesel) APUs weigh about 140 kg, take up about 230 L, and generally cost $500 - $1000 per kW (*29*). Assuming a 3-kW fuel cell APU system (stack and auxiliary components), we calculate that these specifications would equate to targets of about 210 W/kg and 130 W/L. However, noting that the report also states that weight is a limitation on the market potential of these devices (*29*), making these the targets may be overly simplistic. Research at Delphi on diesel-reformed SOFC APUs reports more approachable targets of 50 – 100 W/kg and 50 – 100 W/L (*15*).

Approximately 100,000 heavy-duty tractors are sold annually for line-haul use (*24*).

Summary of APU Applications

Market Size
Above, we identified attractive vehicle markets for fuel cell APUs, and crudely estimated the potential size of the market. Table 5 provides a summary of potential markets. Note that the annual vehicle sales estimates in Table 5 are first estimates. Note also that APUs need not be installed only on new vehicles. In some cases, APUs need to be integrated into the rest of the vehicles' systems, but in some cases retrofits may be plausible and feasible. If retrofitted, the potential markets are much larger.

Packaging, Weight, and Cost Targets
In Table 6, energy, cost, weight, and space targets are summarized for the various vehicle APU applications. These application-specific targets are what is needed for fuel cell APU technology to be cost-competitive with current market alternatives for on-board power generation (expressed as $/kW, W/kg, W/L). As discussed above, we estimated these targets by determining the power size, unit cost, unit weight, and unit volume of the currently available auxiliary power sources. These estimates are indicative and not definitive. They are used only to screen options and develop crude assessments of market potential.

In Table 6, a higher cost ($/kW) target implies that the target will be reached sooner by fuel cell technology, and is therefore a positive sign for a near-term possibility for fuel cells in this application. Conversely, a lower W/kg or W/L target implies target will be reached sooner by fuel cell technology, and is therefore positive for this application.

ASSESSMENT OF FUEL CELL APU UNCERTAINTIES

Fuels and Fuel Cell Technologies
Fuel options for fuel cell APUs could be the pivotal issue in determining where, when, and how fuel cells are introduced. A range of different fuels may be used in fuel cells. Currently, only two types of fuel cells are being seriously considered for vehicular applications: proton exchange membrane (PEM) fuel cells and solid oxide fuel cells (SOFC). SOFCs are only being considered for APU applications since they operate at very high temperatures (800 deg C) and therefore require long start-up times (an hour or more). In APU applications, the fuel cell can be left running most of the time, or could be started far in advance of an anticipated stop. The principal attraction of SOFCs is their relative compatibility with diesel, propane, and other hydrocarbon fuels (*37)*. PEM fuel cells are being developed for vehicle propulsion by a large number of companies and being introduced into vehicle prototypes by almost every major automaker in the world. PEM fuel cells operate most efficiently on hydrogen. A reformation unit may be installed on-board to convert petroleum fuels, methanol, or LPG to hydrogen (or off-board as well, and then can also readily convert natural gas as well), but the reformers add cost and complexity, and reduce energy efficiency. (Another variation is direct-methanol fuel cells.) Increasingly, the attraction of greater availability of petroleum fuel stations is being viewed as insufficient to justify the introduction of non-hydrogen fuel cells. In any case, the fuel issue is critical. In Table 7, we summarize considerations on fuels, fuel availability, and fuel cell technology.

If any fuel other than diesel or gasoline is to be used in the fuel cell, commercialization will be slowed. One strategy for reducing this barrier is the use of centralized refueling, whereby a vehicle returns to the same site for fueling. This obviates the need for a retail fuel network. Vehicles that are centrally refueled are particularly attractive as initial fuel cell users. For instance, as mentioned above, a survey of police fleets revealed that many police cars are or will be purchased that operate on natural gas (28%). This is made possible in large part due to the fact that many police fleets have centralized refueling. The *Vehicle Inventory and Use Survey* reports that centralized refueling is also quite common among heavy-duty truck fleets, especially among larger fleets. Over seventy percent of drivers in fleets over 10,000 trucks reported that they primarily refuel at centralized refueling facilities (*24*). Also, for vehicles that generally travel longer distances, including trips through rural areas, LPG is widely available. Of the applications we have identified, this could be a factor for some RVs, refrigeration units, and line-haul trucks.

Potential Benefits for Fuel Cell APUs

Elsewhere, we have analyzed the potential energy, air quality, and noise benefits of fuel cell APUs, and their cost competitiveness (*33*). The air quality benefits are the result of reducing the use of internal combustion engines and substituting zero emitting fuel cells (or near zero with reformers). The energy (and greenhouse gas) benefits result from the greater efficiency of fuel cells, especially so when compared to idling internal combustion engines (ICEs). And fuel cells are quieter and vibrate less than ICEs as well – especially attractive to sleeping truck drivers and RV owners where RV parks have noise restrictions.

Energy impacts are summarized in Table 8. The highest energy savings result when APUs are utilized for extended periods and accessories draw large amounts of energy, or some combination of these two factors. We have found that a typical trailer refrigeration unit operates for about 2000 hours per year while consuming around one gallon of diesel per hour. Line-haul trucks consume a similar amount of fuel and are idled about 1800 hours per year to power accessory use. There is no comprehensive data on idling and idle fuel consumption for the other applications studied here. Law enforcement vehicles are thought to idle a large amount of the time. Passenger vehicles are likely to idle less and consume less at idle. Because RVs already receive much of their accessory power demand from the electrical grid (and some for direct-firing of LPG), it is unclear the extent to which LPG could improve the net energy consumption.

The economic impacts are even less straightforward, and depend largely on the future of fuel cell costs. Fuel cell APUs are particularly attractive economically when used in place of idling ICEs. They save wear and tear on the engine, and are far more efficient. Idling diesel engines are only about 3% energy efficient, compared to 40% when operating on the highway (*32*).

CONCLUSIONS

This paper presented an initial screening of fuel cell APU market opportunities. We identified seven promising applications: luxury passenger vehicles, law enforcement vehicles, contractor trucks, specialized utility trucks, recreational vehicles, refrigeration units for trailers, and line-haul trucks. Power, weight, volume, and cost targets were specified, and potential market sizes estimated for the candidate applications. In addition we offer qualitative assessments of the advantages and disadvantages of alternative fuels and fuel cell technologies. Each of the identified applications merits further attention, for our research is neither conclusive nor comprehensive. However, we emphasize several findings and recommendations:

- The APU market for refrigeration units and line-haul heavy duty trucks seem particularly attractive; the energy, emissions, and noise benefits may be large, cost benefits (from fuel savings) are relatively large, and large numbers of vehicles are involved.
- Police cars offer a less-studied but promising application for fuel cell APUs with advantages of centralized refueling facilities and receptiveness to alternative fuels.
- Recreational vehicles, despite being widely overlooked in the literature, could prove to be a relatively large and attractive early market, especially if the fuel cells were to operate on widely-available LPG.
- Specialized utility vehicles that use power take-off devices are a diverse and dispersed market, but may be attractive.
- An important next research step is to conduct a cost-benefit analysis of fuel cell APUs and competing alternatives.
- A comprehensive analysis of material and energy flows on-board the vehicle is needed to quantify potential emissions and energy benefits. More data collection of existing prototype systems and on-going fuel cell demonstrations is recommended, along with vehicle system modeling of APU-enhanced systems. More analyses is needed of auxiliary (i.e. non-propulsion) power cost, weight, and volume targets. .

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LIST OF TABLES AND FIGURES

TABLES:

TABLE 1 Major Fuel Cell APU R&D Initiatives

Participants	**Application**	**Size**	**Fuel cell system**
BMW, International Fuel Cells[a]	Passenger car, BMW 7-series	5 kW	Hydrogen, PEM
Ballard, Daimler-Chrysler[b]	Class 8 Freightliner Century Class S/T	1.4 kW	Hydrogen, PEM
BMW, Delphi, Global Thermoelectric[a]	Passenger car	1-5 kW	Gasoline, SOFC
Delphi, CALSTART, Aerovironment[c]	Class 8 truck	5 kW	Diesel, SOFC
SunLine Transit, Southwest Research Institute[d]	Class 8 International Truck	5 kW	
EXCELLSiS[c,e]	Military Class 8 vehicle		Diesel, PEM
DaimlerChrysler, EXCELLSiS[f]	Passenger car, Mercedes S-Class	3 kW	Hydrogen, PEM
Virginia Tech Univ., Energy Partners[g]	Hybrid-electric passenger car	20 kW	Hydrogen, PEM
Department of Defense, U.S. Army[c]	Portable “soldier power”	5-500 W	PEM

(PEM: proton exchange membrane; SOFC: solid oxide fuel cell)
[a] Tachtler, Dietsch, and Gotz, 2000 (3); [b] Brodrick, et al, 2000 (4); [c] Holcomb and Binder, 2001 (5); [d] NAC, 2001 (6); [e] Venturi and Martin, 2001 (7); [f] EXCELLSiS, 2001 (8); [g] Gromatzky, et al., 1998 (9)

TABLE 2 Candidate Fuel Cell APU Applications

Application	APU Loads
Luxury passenger vehicles	· Climate control (heat, A/C) · Electricity for "hotel loads" (lights, windows, defrost) · Communications (phone,GPS) · Full electrification of other systems with 42 V (braking, steering, etc.) [a]
Law enforcement vehicles	· Communications (GPS, radio) · Electricity for "hotel loads" (lights, windows, defrost) · Overhead lights, spot light, sirens, etc. · Full electrification of other systems with 42 V (braking, steering, etc.) [a]
Contractor truck/pick-up	· Generation for power tools (drills, compressors, etc.) · Mobile office capability (computer, communications) · Full electrification of other systems with 42 V (braking, steering, etc.) [a]
Specialized (PTO) utility trucks	· Vehicle-specific device
Recreational vehicles	· Climate control (heat, A/C) · Electricity for appliances (TV/VCR, refrigerator, lights) · Full electrification of other systems with 42 V (braking, steering, etc.) [a]
Refrigeration units	· Trailer cooling of products
Line-haul heavy-duty trucks	· Climate control (heat, A/C) · Electricity for "hotel loads" (TV/VCR, refrigerator, lights) · Full electrification of other systems with 42 V (braking, steering, etc.) [a]

[a] *more long-term possibility than other listed loads*

TABLE 3 Accessory Power Requirements for APUs of Luxury Passenger Vehicle

Accessory	**Power [a] (W)**	**Maximum same-time summer initial APU requirement (W)**	**Maximum same-time winter initial APU requirement (W)**
Rear wiper	90	90	90
Infotronics	100	100	100
Windshield pump	100	100	100
Heated steering wheel	120		
Power sunroof	200		
Truck closer	200		
Windshield wipers	300	300	300
Air pump	400		
Power door locks	400		
Engine coolant pump	500		
ABS pump	600		
Lights	600	600	600
Power windows	700		
Electric fan	800		
Rear defrost	1,000		1,000
Power seats	1,600		
Steer by wire	1,800		
Brake by wire	2,000		
Heated front seats	2,000		2,000
Heated windshield	2,500		2,500
Catalyst heating	3,000		
Electro-mechanical valve control	3,200		
Air conditioning	4,000	4,000	
Active suspension	12,000		
Total	38,210	5,190	6,690

[a] *Krumpelt, 2001 (13)*

TABLE 4 Line-haul Sleeper Truck Power Requirements

Appliance	**Average appliance power (W)** [a]	**Estimated maximum same-time power requirement (W)**
Air conditioner	2,200	2,200
Battery charger	800	
Coffee pot	700	
CD player and speaker	100	
Computer	100	100
Converter	350	
Drill	750	
Fan	100	
Frying pan	1,350	
Stove	1,000	
Water pump	600	
Hair dryer	1,000	
Light bulb	100	100
Microwave	1,500	
Radio	200	200
Refrigerator	350	350
Television	100	100
Toaster	1,200	
VCR	100	100
Total	12,600	2,950

[a] *Values adapted from Venturi and Martin, 2001 (7)*

TABLE 5 Potential Market for Fuel Cell APUs

APU application	Estimated annual vehicle sales (thousand)	Retrofit potential
Luxury passenger vehicles	1,500 [a]	No
Law enforcement vehicles	70-80	No
Contractor truck/pick-up	300	No
Specialized utility trucks	70	No
Recreational vehicles	190	Yes
Refrigeration units	60	Some
Line-haul heavy-duty trucks	100	Yes

[a] *approximately 1,200 thousand cars, 300 light trucks*

TABLE 6 Summary of Target Parameters for FC APUs for Selected Applications

APU application	Peak power requirement (kW)	Approx. APU unit cost ($)	Target system cost ($/kW)	Weight target (W/kg)	Volume target (W/l)
Luxury passenger vehicles[a]	3 – 10	-	~500	50 – 100	50 – 100
Law enforcement vehicles[a]	2 – 3	-	~500	50 – 100	50 – 100
Contractor truck/pick-up[b]	5 – 20	5,000	250 – 1,000	45 – 175	?
Specialized utility trucks	4 – 75	[Diverse uses with large uncertainty in loads, weight, volume]			
Recreational vehicles[c]	2 – 7	2,000 – 4,000	400 – 600	50 – 70	20 – 40
Refrigeration units[d]	10 – 20	3,000	150 – 300	100 - 200	50 – 100
Line-haul heavy-duty trucks[e]	3 – 6	4,000 – 8,000	500 – 1,000	50 -100	30 – 50

(-) *unknown or unavailable data*

[a] *Based on BMW/Delphi estimates (3,15); law enforcement vehicle targets are assumed to be similar to passenger vehicle fleet*

[b] *Based on available data for Dodge Ram Contractor Special and comparable GM pick-ups*

[c] *Ranges are based on available diesel generators for sale for RVs*

[d] *Based on estimates from Carrier on allowable incremental cost, weight, and volume for fuel cell powered refrigeration units and existing refrigeration unit specifications*

[e] *Based on available auxiliary power unit specifications geared for line-haul truck drivers*

TABLE 7 Fuel Considerations for Fuel Cell APU Applications

APU application	Conventional fuel for auxiliary power	Alternative fuel availability [a]	Fueling location	Candidate fuel cell type(s)	Candidate fuel cell fuel(s) [b]
Luxury passenger vehicles	gasoline	-	varied	SOFC	Gasoline
Law enforcement vehicles	gasoline	28%, mostly CNG	central	PEM	Hydrogen, CNG
Contractor truck/pick-up	gasoline, diesel	-	varied	SOFC	Gasoline, diesel
Specialized utility trucks	diesel	some CNG	central	SOFC	Diesel
Recreational vehicles	electricity, propane	LPG	varied	PEM	LPG, diesel
Refrigeration units	diesel	LPG	varied	SOFC	Diesel
Line-haul heavy-duty trucks	diesel	LPG	central or varied	PEM, SOFC	Hydrogen, LPG, diesel

[a] *(-) denotes very little alternative fuel availability*
[b] *assumes gasoline and diesel are either initially, or reformed to, very low sulfur and aromatic content*
(CNG: Compressed Natural Gas; LNG: Liquefied Natural Gas ("propane"); PEM: Proton Exchange Membrane; SOFC: Solid Oxide Fuel Cell)

TABLE 8 Estimated Potential Energy Benefit of Fuel Cell APUs in Given Applications

APU application	Conventional fuel for auxiliary power	Typical Idling fuel consumption (gal/hr)	Accessory power duration	Potential energy benefit with fuel cell APU
Luxury passenger vehicles	gasoline	0.3 – 0.8 [a]	Short	+ [b]
Law enforcement vehicles	gasoline	0.3 – 0.8 [a]	Long	+ [b]
Contractor truck/pick-up	gasoline, diesel	0.5 – 1.0 [a]	Short	+
Specialized utility trucks	diesel	0.6-1.5	Short to long	+
Recreational vehicles	electricity (LPG)	most electric (0.2 – 1.0) [c]	Short	-/+ [d]
Refrigeration units	diesel	0.75 - 1.1	Long (~2000 hrs/yr)	+ [e]
Line-haul heavy-duty trucks	diesel	0.6 - 1.5	Long (~1800 hrs/yr)	+ + [e]

(+) beneficial or positive; (-) less likely benefit
[a] estimate from ADVISOR vehicle modeling program
[b] assumes vehicle electrification of subsystems with 42 V, as discussed above
[c] this is a range of fuel consumption for diesel APUs purchased by RV owners
[d] improvement for propane-utilizing appliances (stoves, heating), but electric appliances powered by grid may not see improvement in efficiency
[e] although consumption, accessory duration are similar for refrigeration and line-haul idling, the engines have vastly different operating efficiencies for these applications