Fuel Cells, the Hydrogen Economy, You and Your Company

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Introduction

Politicians and environmental activist groups throughout the world are advocating the use of fuel cells and hydrogen to reduce oil imports and improve the environment. As with all complex undertakings with economic, social and political components, the discussion and hopes range from realism to fantasy. Since the fuel cell field is developing rapidly, many companies, academic and governmental laboratories, and individual engineers wish to participate. It, however, is not always clear which of the numerous activities required for the development, production and deployment of fuel cells and their fuels most closely match the abilities and goals of any particular party. An overview of the current status and challenges, together with predictions, is presented below to assist companies making investment decisions and engineers evaluating career possibilities.

Fuel cells are devices that convert the chemical energy in fuels to electricity. Although invented accidentally in 1839 during a mix-up in an electrolysis experiment, the first practical fuel cells were developed only in 1950. Continual improvements lead to their use in specialized situations such as the Gemini Titan XII (1966) and Apollo 13 (1970) and the newer Orbiter spacecraft. An enormous amount of research and development work is underway throughout the world, and they are now practical for a somewhat wider range of applications.

Electricity may, of course, be generated by numerous methods, including boiler/steam turbine systems, internal combustion engine-generators, hydro, pumped and compressed air systems, conventional and flow batteries, and fuel cells. Each has advantages and disadvantages, generally centered on economic, reliability and environmental issues.

Fuel cells have thermodynamic and environmental advantages over combustion-based processes such as boiler/steam turbine or diesel engine generation. Since fuel cells can use hydrogen as a fuel, they are viewed by many as the most promising way to substantially reduce air pollution problems and to reduce the need for crude oil from unfriendly and unstable countries. These are unlikely to occur for several decades. Fuel cells do have a promising future, but because they offer other advantages.

Advantages of Fuel Cells

High Efficiencies: The context of "efficiency" needs to be clearly understood.
- ❑ A user will generally base it on only net electrical output per unit of fuel used by the fuel cell system.
- ❑ Those concerned with broader issues such as the global or national energy and environmental matters will adjust these for the energy needed to produce, purify and distribute the fuel. These, particularly in the case of hydrogen, are substantial factors. If the raw fuel is a hydrocarbon, the overall well-to-fuel

cell system efficiency might be 50 to 85 percent of that reported only for the fuel cell system.

The efficiencies[1] of the low temperature units (except alkaline) are generally between 40 and 47 percent. These are not noticeably higher than the 45 percent value typical of a heavy duty truck diesel engine, and do not reach the 54 percent attained by a large modern gas turbine-based combined cycle power plant[2] or the 52 percent by a large modern diesel engine-based power plant.[3] They, however, do not drop at part-load operation, but are maintained at all load points between 15 and 100 percent of rated output.

High temperature units, without heat recovery, may exhibit approximately the same efficiencies attained by a large modern gas turbine-based combined cycle power plant or a large modern diesel engine-based power plant. If a bottoming cycle is added, the efficiency of a fuel cell based power plant may actually far exceed that of one using conventional technologies. As noted above, the efficiency does not drop at part-load operation.

Efficiencies of fuel cells fall noticeably with use, particularly for high temperature units, as electrical interconnections and sealing systems degrade. Catalyst systems also lose their effectiveness through poisoning, oxidation and sintering that reduces active sites. Efficiency reductions of approximately 2 percent per year have been reported.

Required efficiency is, moreover, a moving target as even relatively mature technologies continue to evolve. Modern diesel engines, for example, are benefiting by operating at higher compression ratios than previously, and much effort is being devoted to developing ceramic combustion turbine components that will operate at higher temperatures and hence yield higher efficiencies.

Interestingly, an ethanol-fueled internal combustion engine-powered car[4] achieved the best fuel efficiency and produced the lowest greenhouse-gas emissions at the European Shell Eco-marathon 2006 in Nogaro, France. Energy consumption was equivalent to a remarkable 2,885 kilometers per liter of gasoline. A fuel cell competitor "only" attained 2,730 kilometers per liter of gasoline. The winner in 2005, however, was a hydrogen fuel cell-powered car that achieved a usage equivalent to 3,836 kilometers per liter of gasoline.

As with conventional electricity generation technologies, recovery of otherwise wasted heat for use in cogeneration and bottoming cycles is technically possible. Characteristics of the main types of fuel cells are presented below. It will be seen that relatively small amounts of thermal energy, in the form of hot water or very low pressure steam, may be

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[1] Electrical energy produced per unit of fuel energy used (on a lower heating value basis)
[2] GE LMS100, 100 MW
[3] Wartsila-Sulzer RTA96C: 2-stroke low speed turbocharged, 81,470 KW, 0.261 Lb fuel oil / Hp-Hr
[4] 1-person, 3-wheeled light weight vehicle, driven for 25 kilometers
  at an average speed of 30 kilometers per hour

recovered from alkaline, PAFC or PEM fuel cells because they operate at low temperatures. Conversely, since MCFCs and SOFCs operate at high temperatures, it is practical to generate high pressure steam from their exhaust gases for producing additional electricity from a steam turbine-driven generator, or for process use. The best approach to recovering and using waste heat will depend on project-specific factors, including economic and space considerations.

Air Pollutant Emissions: Virtually the only emissions from fuel cells are nitrogen oxides, carbon monoxide, carbon dioxide and water vapor. The exact amounts, of course, depend on the nature of the fuel and the type of fuel cell being used. As with efficiency, consideration may be focused narrowly on the direct emissions from the fuel cell, or the additional emissions from the fuel production, purification and transportation processes may be included. Emissions of NOx from fuel cells may be as low as 0.3 ppmv which is less than 10 percent of those from gas turbines fitted with selective catalytic reduction systems. Emissions of carbon monoxide and unburned hydrocarbons are also very much lower than from engines, turbines or boilers. Sulfur dioxide emissions will be virtually undetectable since the fuel must be desulfurized prior to entering a fuel cell.

Reducing carbon dioxide emissions is becoming increasingly important as pressures to meet Kyoto Protocol goals gain momentum. Fuel cells produce similar or slightly lower carbon dioxide emissions than do combustion-based technologies when calculated on a "per kilowatt-hour" basis, as a result of their somewhat higher fuel-to-electricity conversion efficiencies.

Recognizing their superior emissions performance, some jurisdictions[5] exempt fuel cells from air permitting requirements. A Water Diversion or Allocation Permit, and a Water Discharge Permit may, nevertheless, be required for projects in the several hundred kilowatt and larger sizes.

> *Although fuel cells do indeed offer very low emissions, it must be emphasized that the production of fuels, particularly hydrogen, is energy intensive and uses processes that emit substantial amounts of pollutants and greenhouse gases.*

Extremely High Reliability: Fuel cells, unlike internal combustion engines and turbines, have no inherently moving parts. As with other generation technologies however, their support systems do often rely on external components such as cooling water and process water pumps, and blowers or fans, and on electronic components within control systems.

NASA has developed sufficient confidence in alkaline fuel cell's reliability that it does not provide battery backup capability on manned Orbiter satellites; 99 percent availability has been demonstrated during 82,000 hours of operation on 106 missions. Furthermore, they provide the only source of drinking water for astronauts. PEM fuel cells are also used for the "air independent propulsion" systems that allow long-endurance slow speed

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[5] The States of Connecticut and Massachusetts, and the South California Air Quality Management District

underwater patrols by many of the new electric motor-driven submarines that various countries have deployed throughout the world.

A PEM fuel cell system[6], fueled from local cylinders of gaseous hydrogen at McChord Air force Base, Tacoma, WA, operating since April 17, 2003 has demonstrated 1106 successful starts out of 1111 attempts; 99.5 percent system availability. The availability of the fuel cell was 100 percent; failures arose in the balance-of-plant components.

Many backup and standby systems rely on batteries to provide electrical energy during power outages or to start Diesel engine-driven generators.   The battery systems, unfortunately, have proven to be very unreliable. A large scale study[7] of 742,587 cells showed that only 67 percent could be relied on during the first four years after installation. A 48-volt system consisting of four 12-volt units connected in series can reasonably be expected to be available only 20 percent of the time; i.e., not available 80 percent of the time. Battery life, moreover, is adversely affected by high ambient temperatures. A 10 degree C increase in temperature typically decreases battery life by 50 percent.

Not all experience in real world situations, however, has been positive. A comparison[8] of the performance of three fuel cell propelled buses and five Diesel engine-driven buses is summarized on Figure 1.   While the Fuel cell buses attained 1,044 miles between propulsion related road calls, the Diesel buses reached 11, 424 miles. Obviously the situation will improve in time, but much has to be accomplished. It is also noted that the fuel efficiency of the fuel cell buses is 13 percent lower than that of the Diesel buses, on an energy basis. This, moreover, is limited to the as-fueled buses. If consideration is given to the production and liquefaction of the hydrogen for the fuel cell, the difference is a far greater 45 percent.

High Power & Long-duration Power per Size:
Actual performance and lifetimes of batteries depend on the discharge rates and number of discharge/recharge cycles to which they are subjected. Fuel cells nevertheless clearly have substantially higher energy delivery capacities than do batteries, as shown on Table 1.

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[6] ReliOn , Inc., Spokane, WA, USA

[7] Miller, J. and M. F. De Anda, Reliability of Valve-Regulated Lead-Acid Batteries for Stationary
   Applications, EESAT 2002 Conference, San Francisco, California, April 17, 2002

[8] Eudy, L., National Renewable Energy Laboratory, NREL/PR-540-40012, Presented at
   APTA Bus and Paratransit Conference, Anaheim, California, May 2, 2006

Figure 1
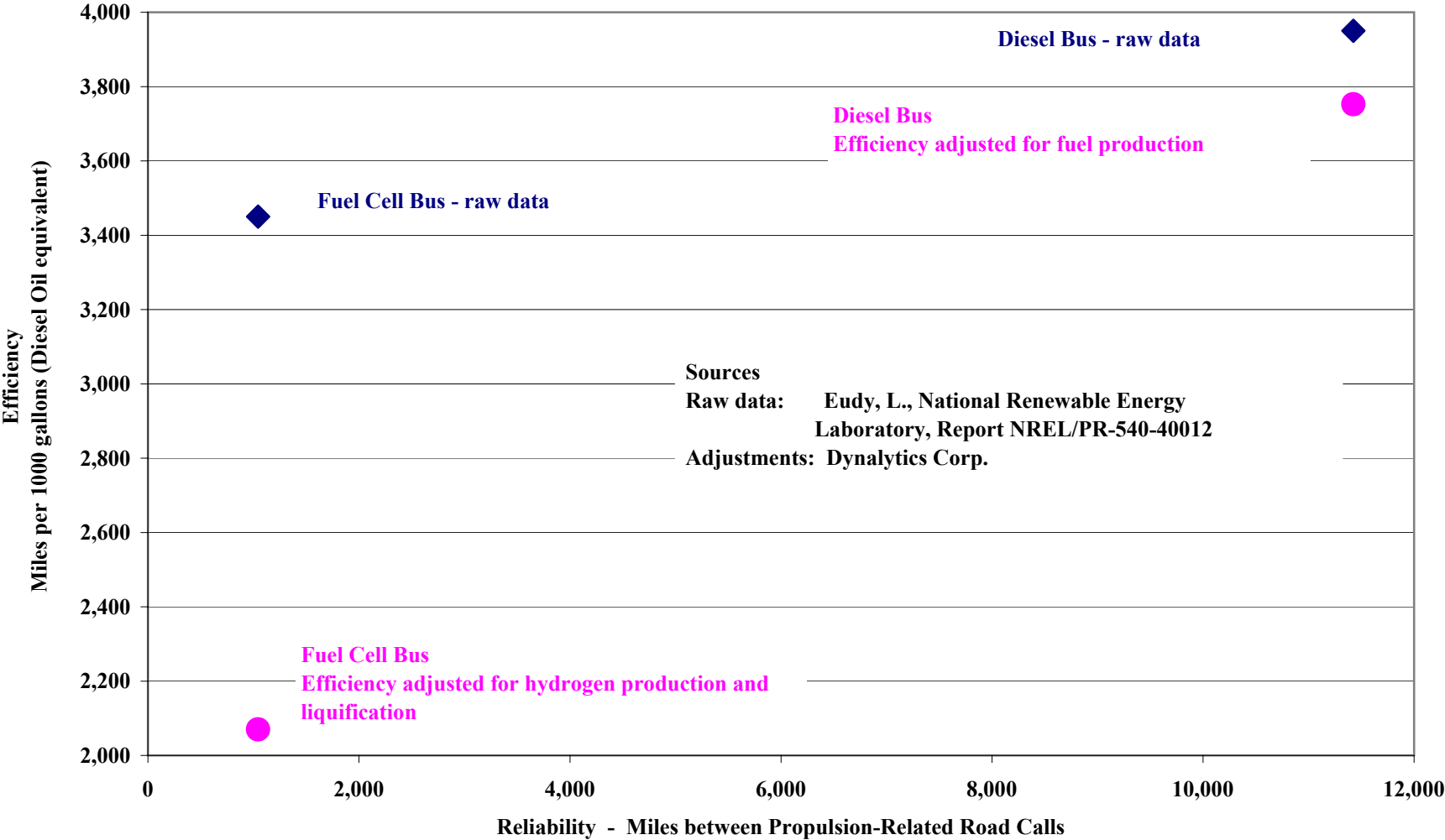**Efficiency and Reliability**
Fuel Cell Bus vs. Diesel engine Bus

Table 1

Technology	Specific Energy Delivery Watt-Hours / Kilogram
Lead-Acid	30-50
Nickel-Cadmium	45-80
Lithium Ion	110-160
Reusable Alkaline	~ 80
Cylinder with 136 atmosphere H_2	150
Cylinder with 680 atmosphere H_2	700
Tank with Liquid Methanol	6,100

Quiet Operation: Fuel cells produce electricity extremely quietly since they do not use the explosions that occur in diesel engines or have moving parts such as pistons or turbine shafts (with the possible exception of auxiliary components.) This is advantageous in many commercial and industrial situations. Fuel cells that provide backup power for computer systems, for example, may be placed and operated within office buildings; this is not practical for a diesel engine-powered generator system. Quiet operation is particularly beneficial for military applications such as "silent watch" and submarine propulsion.

Relaxed speech is readily intelligible with a background noise level of 45 dBA, and if spoken moderately louder with a background noise level of 55 dBA. Simple fuel Cell systems up to a few kilowatts typically emit noise levels of 35 to 53 dBA at one meter. These levels are readily reduced by providing noise barriers or acoustic insulation if necessary. Larger and more complex systems are noticeably noisier. The 200 kilowatt PAFCs typically emit noise levels of 60 dBA at 18 meters; the 250 kilowatt MCFCs typically emit noise levels of 72 dBA at 3.3 meters. These levels may also be reduced by providing noise barriers, air inlet silencers and similar items if necessary.

Remote Status Monitoring: It is relatively easy to measure the temperature and pressure of the contents of a gas cylinder, transmit the data electronically, and calculate the amount of useable hydrogen remaining to be used, and hence the remaining electrical energy available. Similarly, the height or weight of a liquid fuel is readily measurable and can be transmitted and processed to determine the remaining energy supply. This assessment of remaining capacity can therefore also be done for diesel engine systems, but cannot be accurately done for batteries.

Technical Matters - Fuels

Fuel Processing: Many raw fuels such as hydrocarbons, alcohols and ammonia must be converted to hydrogen or possibly carbon monoxide before they can be used in a fuel cell. There are many variations, but the following processes, shown on Figure 2, may be utilized or required.

- ❑ Fuel desulphurization
- ❑ Raw hydrogen production
- ❑ Hydrogen purification
- ❑ Preparation for storage and distribution

These processes may require more equipment and complex control systems than is readily apparent. Depending on the fuel and the fuel cell type and capacity, vaporizers, heat exchangers, humidification/drying systems, pumps and blowers may be necessary.

Since fuel is not completely consumed, unreacted fuel must be recovered in the 100^{+} kilowatt systems to produce acceptable economic performance. This requires recycle compressors, piping and control systems, and possibly water removal equipment.

There is much experience with designing, constructing and operating large-scale fuel and hydrogen production facilities. Much of this, however, is not applicable to the quite small systems desired for many fuel cell applications. A great many groups throughout the world are therefore developing processes and equipment that are compact, durable, adequately efficient, and cost-effective for this application. Important examples include miniature reforming and purification systems, improved catalysts, and new approaches to heat integration; there are major challenges.

Fuels: Today's fuel cells most commonly use hydrogen as the fuel. It has a very high energy[9] density on a "per weight" basis (Figure 3,) but a very low one on a "per volume" basis (Figure 4.) Carbon monoxide may also be used as the fuel in very high temperature fuel cells. Either of these may be produced externally from a wide variety of materials, using a variety of technologies. Alternately they may be produced directly within the fuel cell assembly (internal reforming) by using a number of chemical engineering technologies.

Hydrogen, at a purity acceptable for use in a fuel cell, is readily available from numerous commercial sources. It may be produced, delivered and stored in various ways that are discussed below.

Energy usage and production data are presented in the following as "kilocalories per kilogram of hydrogen." One kilogram of hydrogen can produce 27.1 kilowatt-hours of electricity from a thermodynamically perfect 100 percent efficient fuel cell. Although there are significant variations, heat losses in the effluent gases, parasitic losses and unreacted fuel cause actual efficiencies to currently be approximately 40 percent.

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[9] Energy content is the Gibbs free energy, which determines the maximum electrical energy obtainable
from the fuel under ideal conditions

Figure 2
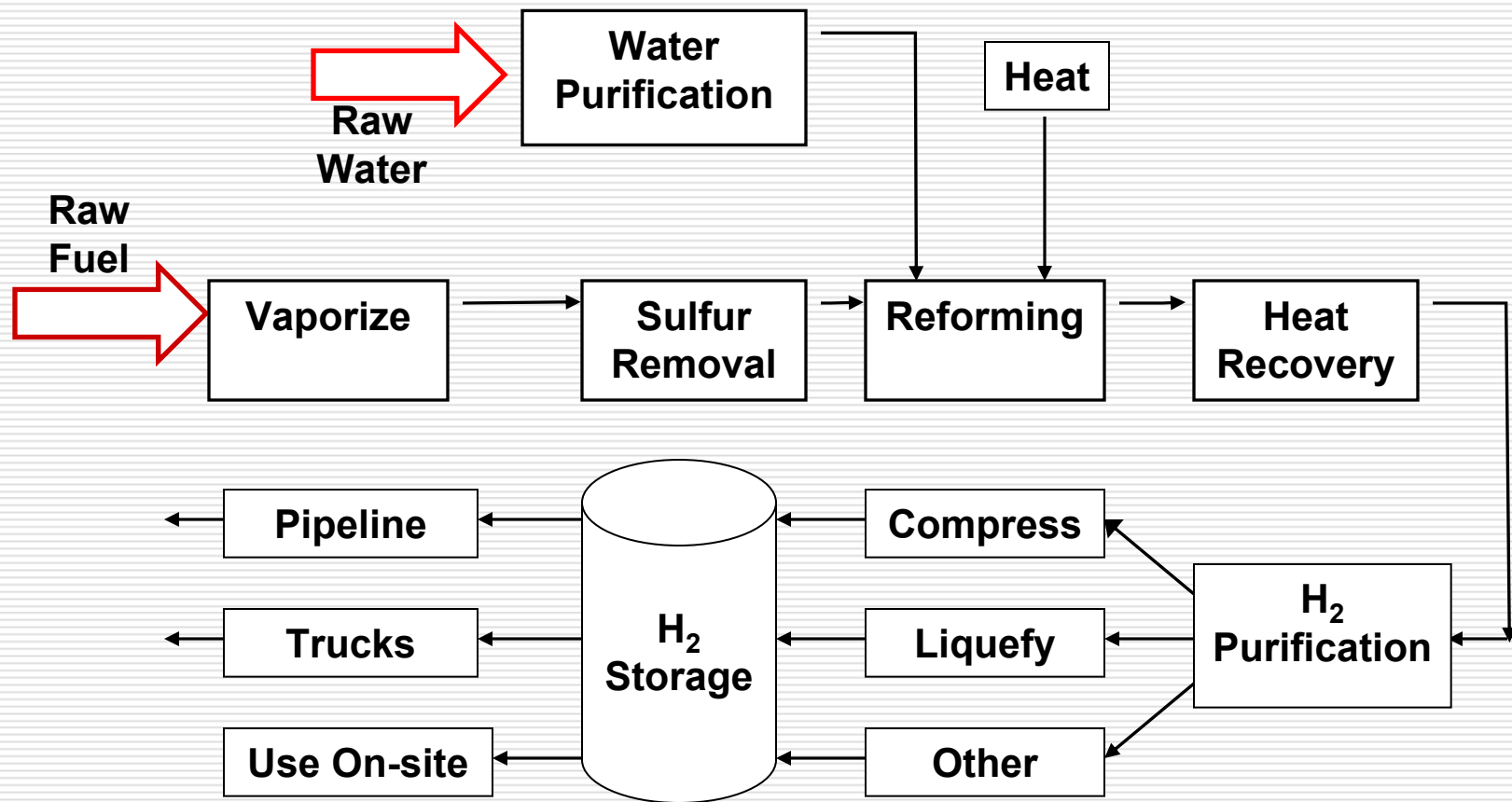# Hydrogen Production & Distribution

Figure 3
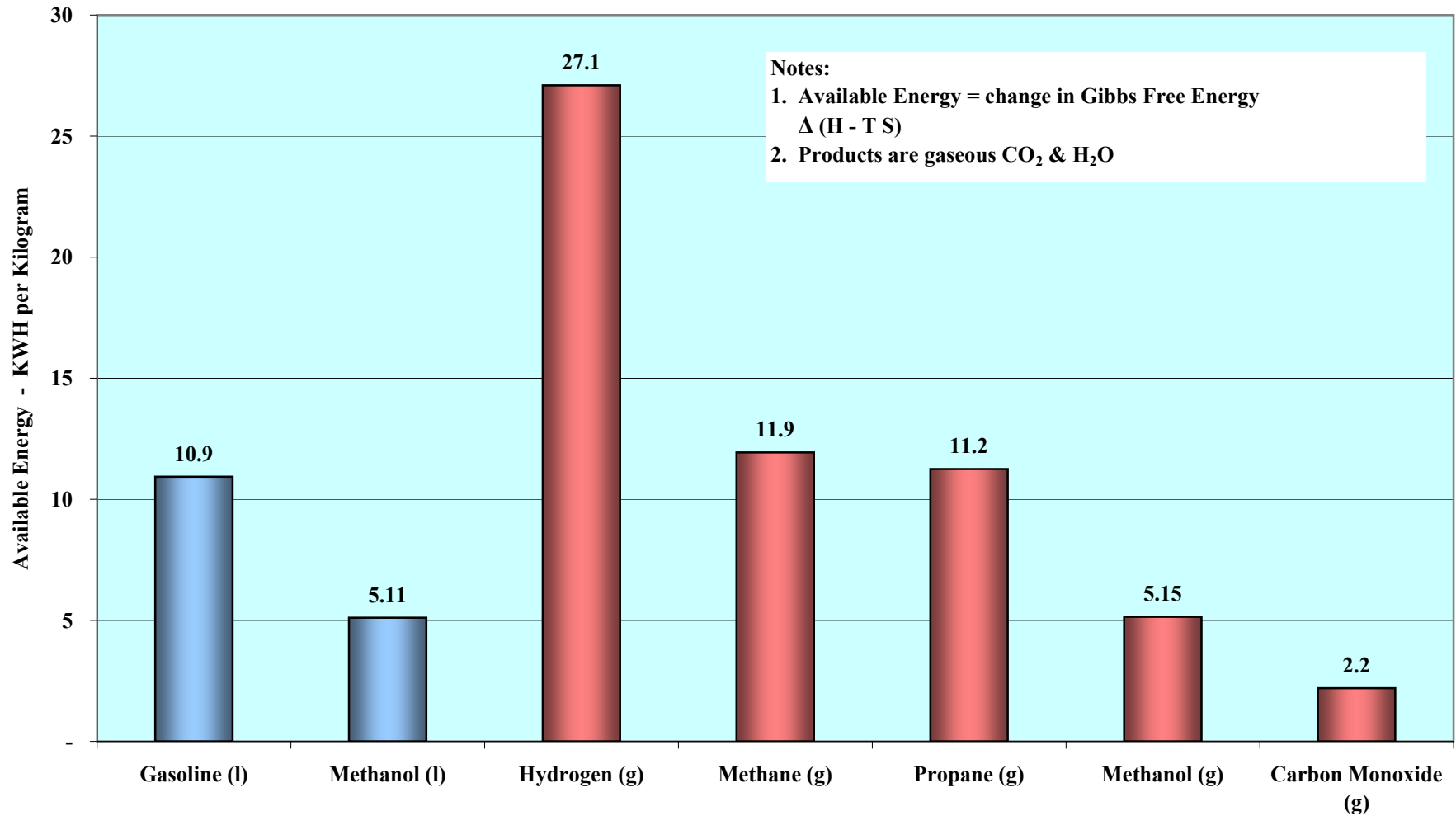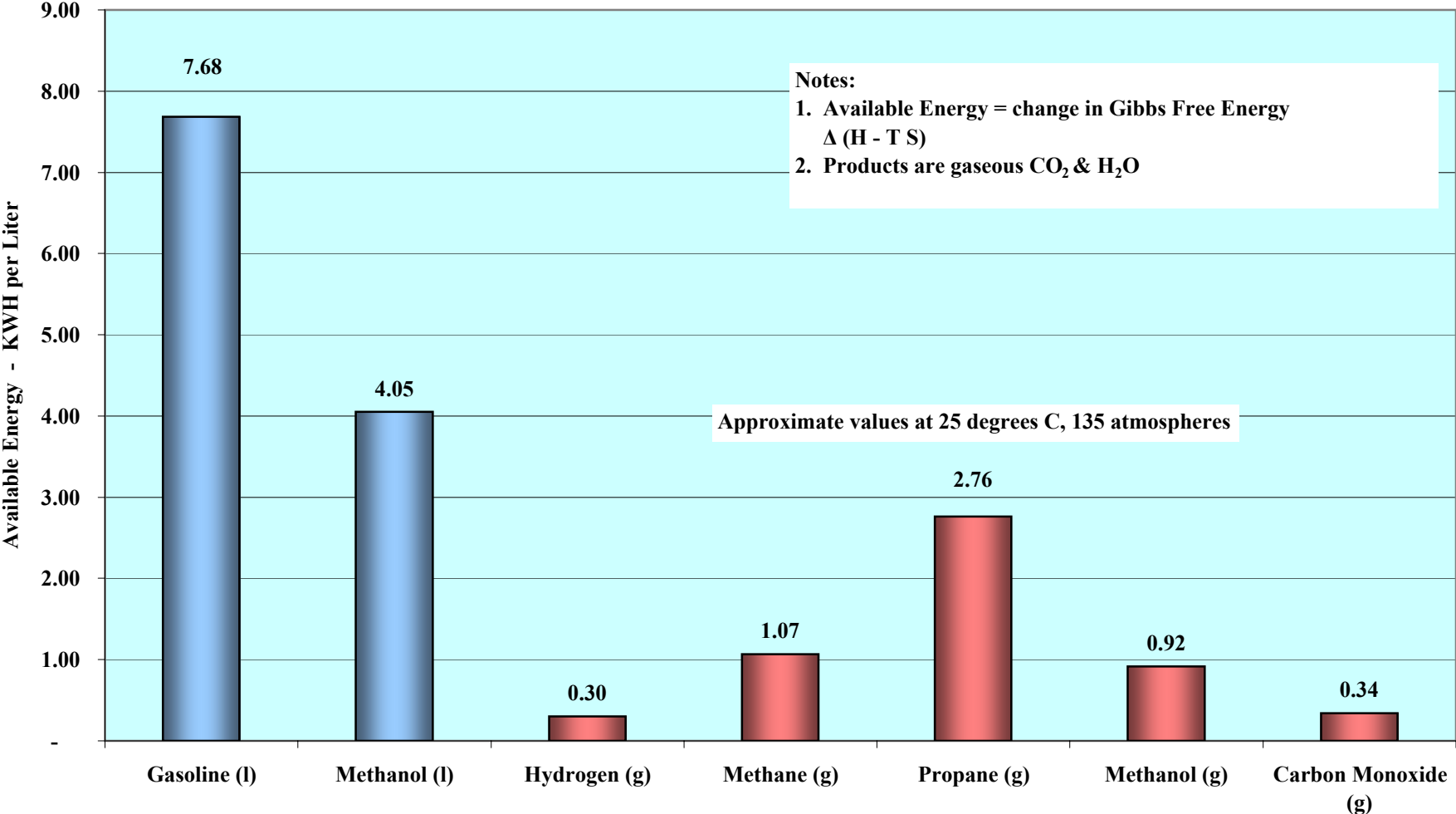**Electrical Energy Available from Fuels**
on a _Weight_ Basis

Notes:
1. Available Energy = change in Gibbs Free Energy
   $\Delta (H - T\,S)$
2. Products are gaseous CO_2 & H_2O

**Figure 4
Electrical Energy Available from Fuels
on a <u>Volumetric</u> Basis**

Notes:
1. Available Energy = change in Gibbs Free Energy
   $\Delta (H - T S)$
2. Products are gaseous CO_2 & H_2O

Approximate values at 25 degrees C, 135 atmospheres

Available Energy - KWH per Liter

Fuel	Value
Gasoline (l)	7.68
Methanol (l)	4.05
Hydrogen (g)	0.30
Methane (g)	1.07
Propane (g)	2.76
Methanol (g)	0.92
Carbon Monoxide (g)	0.34

Electrolysis

Very pure hydrogen, together with byproduct oxygen, may be produced from water by electrolysis.[10] This is a relatively mature technology that may fill a special niche in production of electricity from fuel cells. The "round trip" from electricity to hydrogen and then back to electricity may not be thermodynamically elegant, but may be economically advantageous if the electricity for electrolysis is obtained at very low cost such as from photovoltaic cells, wind, waves or similar sources, at times or locations for which it can not be economically transmitted to an electric grid. The hydrogen produced may then be stored and used as in a fuel cell at an appropriate time. This is conceptually similar to pumped storage or compressed air storage systems.

The thermodynamically minimum amount of energy required for electrolysis is 3145 kilocalories per kilogram of water. Modern electrolysis systems have efficiencies of 80 to 90 percent, but rely on direct current. The efficiency loss and capital cost of the AC-to-DC converter must also be considered in an evaluation of the overall electrolysis system. Hydrogen may be produced by electrolysis at very high pressures, and with purities exceeding 99.9999 percent. Additionally, it may be economically attractive to recover the byproduct oxygen; a project-specific evaluation must be performed.

The energy required for electrolysis may be reduced by operating at high temperatures. Development work[11] has demonstrated that electrolysis at 1000 degrees C will provide total energy savings (including the energy required to produce the electricity,) of approximately 35 percent vis-à-vis operating at ambient temperature. Many problems must be overcome, such as those associated with durability, sealing and corrosion resistance, before high temperature electrolysis will be commercially practical.

Thermochemical cycles

Hydrogen may also be obtained from water by using thermochemical cycles. One promising technology is the iodine-sulfur (IS) process, in which sulfuric acid is decomposed at 800-1000 degrees C, producing water, sulfur dioxide and oxygen. The sulfur dioxide is then reacted at 120 degrees C with iodine and water to produce hydrogen iodide (HI) and sulfuric acid that is recycled. Finally, the HI is dissociated at 350 degrees C to produce the desired hydrogen and iodine that is also recycled. There is virtually no net consumption of the sulfuric acid or iodine after recovery and recycle. This and similar thermochemical processes are being evaluated by several groups[12] as adjuncts to nuclear reactors that may be economical sources of the high temperature thermal energy that is required.

Using water as a raw material, whether with electrolysis or with thermochemical cycles, is not free of economic and political drawbacks. Water shortages are a serious problem in much of the world, including the Southwestern United States.

[10] For example: Proton Energy Systems, Wallingford, CT, USA
[11] Idaho National Laboratory and Cermatec, Inc.
[12] Scandia National Laboratory and CEA (France), General Atomics (U.S., Japan Atomic Energy Authority

Hydrogen may also be extracted from hydrocarbons externally or internally within the fuel cell system by any of a number of processes as follow.

Steam Hydrocarbon Reforming
Hydrocarbons such as methane, propane, liquefied petroleum gases (LPGs) and naphtha may be mixed with steam and passed over catalysts, typically a nickel or rhodium-based material, placed within highly alloyed heat resistant tubes or between flat plates. Hot combustion gases flowing on the outside of the tubes or plates transfer heat to the reacting mixture, typically raising their temperatures to approximately 700 to 850 degrees C. Pressures of 3 to 27 atmospheres are commonly used. The chemical reaction for methane is:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
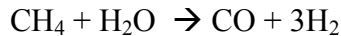
This reaction is endothermic (absorbs heat) requiring a heat input of 8137 kilocalories per kilogram of H_2 produced. The hot process stream leaving the reformer contains hydrogen, carbon monoxide, excess steam, carbon dioxide formed as a byproduct and unreacted methane.

Other fuels may be reformed at lower temperatures. Methanol, for example, may be reformed at temperatures of 250 to 350 degrees C over copper/zinc catalysts, according to the following overall reaction.

$$CH_3OH + H_2O \rightarrow CO_2 + 3H_2$$

This reaction is endothermic (absorbs heat) requiring a heat input of 1930 kilocalories per kilogram of H_2 produced.

As with other feedstocks, the hot process stream leaving the reformer contains hydrogen, carbon dioxide, excess steam, carbon monoxide formed as a byproduct and unreacted methanol.

Undesirable carbon and soot may also form on the nickel catalyst if inadequate steam or too low temperatures are used. This will lead to lowered catalyst effectiveness, shortened catalyst life, and the need to operate at even higher temperatures which adversely impact component life and system efficiency.

The thermal efficiencies of steam hydrocarbon reforming systems are typically between 75 and 80 percent, depending on the composition of the hydrocarbon feed and the extent of heat recovery.

Partial Oxidation
Alternately, hydrocarbons may be partially oxidized by burning them with quantities of air or oxygen that are insufficient for complete combustion, and with no or very little steam present. The chemical reaction for methane is:

$$CH_4 + \frac{1}{2} O_2 \rightarrow CO + 2H_2$$
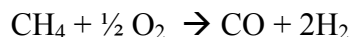
The oxidation reaction is exothermic, releasing 2,131 kilocalories per kilogram of H_2 produced. Although catalysts are not required, they are frequently used to increase the yield of hydrogen relative to carbon monoxide. This approach is also well established and offers several advantages. For example since the reaction is exothermic no heat

exchange equipment is needed, leading to more compact units. Needing no, or very little, steam is another important advantage where water is scarce. Partial oxidation, however, has the disadvantages that the product gases are diluted by nitrogen from the combustion air (unless pure but costly oxygen is used) and the carbon dioxide that is produced. Furthermore, the purge gases from the purification sections have little use as a fuel. Additionally the combustion air must be compressed to the oxidation reactor pressure.

The thermal efficiencies of partial oxidation reforming systems are typically between 70 and 75 percent, depending on the composition of the hydrocarbon feed and the extent of heat recovery.

Autothermal Reforming
Another practical process combines partial oxidation with steam hydrocarbon reforming. A partial oxidation process is carried out immediately upstream of a steam hydrocarbon reforming process. The former provides the heat of reaction for the latter, and the combination leads to a physically compact system. The combination however requires a larger downstream purification system.

Several other liquid fuels such as propane, liquefied petroleum gas (LPG), kerosene, gasoline, ethanol and, most notably, methanol have also been used successfully to produce hydrogen for use in fuel cells.

All three hydrocarbon reforming processes produce gases that, while having noticeably different compositions, are relatively rich in hydrogen, carbon dioxide and carbon monoxide.

Non-hydrocarbon fuels: If one focuses on energy security and proven reserves of primary fuels, the most attractive fuel in North America, much of Europe and Asia is coal. Although there are huge reserves of coal, its use brings many well known disadvantages, including variable compositions, corrosive and catalyst-poisoning impurities, reliance on high maintenance materials-handling systems, and the life-threatening dangers of coal mining. Additionally, its resulting pollutants are expensive to control and emissions include carbon dioxide which is a greenhouse gas.

Efforts to use coal follow two paths. One approach is to gasify the coal to produce carbon monoxide and hydrogen, exemplified in the United State's FutureGen program. This $1 billion dollar initiative will seek to design, construct and operate a 275 megawatt prototype plant that integrates the production of electricity and hydrogen, produces near-zero emissions and captures 90 percent of the carbon dioxide emissions. Economic goals are to produce electricity at a cost that is not more than 10 percent above that from conventional plants, and to produce hydrogen at $4.00 per million BTUs ($16.00 per million kilocalories); these are aggressive.

The second path is to use carbon directly in a fuel cell. This is potentially more efficient than other approaches, but has all of the mechanical problems of SOFCs, which are made

more difficult by the nature of coal. Many groups[13] are developing this technology, but it is unlikely that practical systems will be available within the next fifteen years.

Hydrogen may also be obtained by cracking ammonia, which is relatively easy to transport and store. This cracking technology and its integration into operational fuel cells have been demonstrated.[14] The chemical reaction is:

$$2NH_3 \rightarrow N_2 + 3H_2$$

This reaction is endothermic (absorbs heat) requiring a heat input of 3624 kilocalories per kilogram of H_2 produced.

Other possible near-term fuels include formic acid (CHO-(OH)) and hydrazine (N_2H_4) which also has been used in fuel cells, but is generally considered too dangerous and too toxic for wide spread use.

In the longer term, microbial-based fuel cells using sugars, celluloses or green algae may become practical. These are the subjects of various academic investigations.

Purification

Hydrogen purity is important for two reasons. Firstly, various catalysts may be poisoned by compounds such as sulfur, carbon monoxide, and unsaturated hydrocarbons; the effect is temperature- and catalyst-specific. Natural gas as delivered from pipelines in many countries is legally required to contain odorizers for safety reasons. These are most often sulfur-bearing compounds. Similarly, commercial propane is commonly supplied in accordance with ASTM D1835, which allows up to 185 ppmv of H_2S and total sulfur. These cause problems since they poison many reformer and the fuel cell catalysts.

Platinum electrode catalysts are poisoned at low temperatures (<200 degrees C) by carbon monoxide, which is therefore typically limited to concentrations of less than 10 ppmv. Although performance will be impaired, the poisoning is reversible.

Impurities may be removed by numerous proven techniques such as hydrodesulphurization, molecular sieves (zeolites) or reaction with zinc oxide, iron oxide or copper impregnated adsorbents. Each has a logical niche, and each brings capital and operating cost penalties.

Operating cost is a second factor when considering hydrogen purity. Unit costs of hydrogen in cylinders for small and midsized applications certainly vary with specified purities. Typical values in mid-March 2006[15] are approximately as shown on Table 2.

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[13] See for example: Cooper, J., Lawrence Livermore National Laboratory, SRI International, American Electric Power, Clean Coal Energy, LLC and CellTech

[14] Apollo Energy Systems, Inc., Pompano Beach, FL, USA; Argonne National Laboratory (2005)

[15] Scott Specialty Gases, 196 standard cubic feet, 2,000 psig (5,500 normal liters, 136 atmosphere) cylinders

Table 2

Hydrogen Purity Volume Percent	Unit Cost $ / SCF
99.95	0.30
99.99	0.35
99.999	1.50
99.9995	1.60

The undesired carbon monoxide from reforming processes is frequently reacted with steam, over catalysts in "shift reactors", to produce additional hydrogen and carbon dioxide, according to:

$$CO + H_2O \rightarrow H_2 + CO_2$$
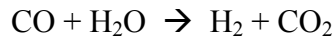
This reaction is exothermic, releasing 9.823 kilocalories per mol (28.000 grams) of CO reacted or mol (2.016 grams) of H_2 formed. It is frequently carried out in two intercooled stages over a Cu/ZnO/Alumina catalyst to produce additional hydrogen (and carbon dioxide.) A high temperature stage operating at 350 to 475 degrees C is followed by cooling, and then a low temperature stage operating at 200 to 250 degrees C. The catalysts, however, are subject to poisoning by chlorine or magnesium/aluminum compounds.

The process stream leaving the shift reactor contains residual carbon monoxide which may then be removed by preferential catalytic oxidation to carbon dioxide or, if present in small amounts, reacted catalytically with hydrogen to form methane.

The hydrogen may then be further purified if necessary, again by using any of the many well established processes. In practice, molecular sieves or semi permeable palladium membranes that allow hydrogen to pass through them while blocking other compounds are most often used within integrated fuel cell systems. These can readily accept feeds with initial hydrogen contents of 25 percent or higher and produce a hydrogen product with a 99.999 percent purity.

In addition to the catalysts used within the fuel cells themselves, various other catalysts used to produce and purify hydrogen are susceptible to poisoning by certain chemicals. Fuel cell vendors thus limit the compositions of the raw materials fed to their systems. Although equipment-specific, particular concerns exist about:

- Alkali metals
- Ammonia
- Carbon monoxide
- Halogenated compounds
- Nitrogen
- Sulfur compounds
- Unsaturated hydrocarbons

Several *Standards* for hydrogen composition have been developed[16] for uses ranging from general industrial applications (99.95 percent H_2) to semiconductor production (99.9997 percent H_2.) Compliance with these standards however may not assure adequate performance of fuel cells or storage systems. It is very important to ascertain from the fuel cell vendor what the acceptable levels of contaminants are for its particular fuel cell design, and to then assure that these levels will not be exceeded by the fuel supplier. Indeed, one major fuel company indicated in a recent presentation that "*At their current stage of development, fuel cells are extremely sensitive to impurities, leading to hydrogen requirements for demonstration projects which are, in some cases, beyond the limit of conventional detection. Consequently, BP spends almost $4,000 each time we want to verify that our hydrogen meets the requirements of fuel cell manufacturers. It we are ever to reach commercial reality then this has to change.*"[17]

Typical limits are as follows.

        CO: SOFC No Limit (CO may be a fuel)
               PAFC < 500 ppm (0.05 percent)
               PEM   < 10 ppm

        Sulfur SOFC < 1 ppm
                PAFC < 500 ppm
                MCFC < 0.5 ppm

The technical and economic difficulties of producing and transporting hydrogen have led to searches for alternate fuels. The most promising candidate at this time is methanol which may be reformed at relatively lower temperatures of 260 to 320 degrees C, or may be used directly as a pure liquid or in dilute aqueous solutions. Liquid methanol has, as shown on Figures 3 and 4, a reasonably high energy density on both a weight and volumetric basis. It is mostly produced from natural gas but, importantly, has also been produced from coal. During a 69-month demonstration project,[18] 105,000 liters per day were produced with a plant availability of 97.5 percent.

Although methanol is reasonably attractive with respect to energy density, ease of transport and storage, it does have some disadvantages. The most common feedstock for its production is natural gas, although other hydrocarbons are also used. Additionally, the use of the black liquor waste product from the pulp and paper industry has been shown[19] to be technically possible on a pilot plant scale, but its competitive situation is not yet clear. Conversion efficiency, on an energy basis, is typically only approximately 70 percent, versus 85 percent for hydrogen production. On an overall basis, its production and use therefore increases the total amount of hydrocarbons that would be used. Methanol is moderately corrosive at ambient temperatures, requiring grade 304 stainless

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[16] GGA G-5.3, JIS K0512, MIL-PRF-27201C, Title 13 CCR §2292.7
[17] Battershell, B., Vice President, Renewables & Alternatives, BP Gas and Power, Presentation to the National Hydrogen Association, 30 March 2005
[18] Clean Coal Technology Project: Air Products and Chemicals Inc., and Eastman Chemical Company
[19] Nykomb Synergetics, Sweden

steel storage tanks, piping and wetted pump and valve components. It is also a toxic material that is soluble in water. At the higher temperatures encountered in vaporizers and reformers, more highly alloyed (> 60 percent nickel) components, with their cost penalties, are required for adequate corrosion resistance. Since chlorides and high-boiling-point compounds may lead to problems, a dedicated distribution system may be required for methanol.

Ethanol is another major contender. Relatively small amounts of it are produced by hydration of ethylene that has been produced from natural gas or other hydrocarbons. The majority of ethanol is currently being made from various cellulosic materials such as sugar cane in warm climate regions and, somewhat less economically, from corn in cooler areas. Demonstration projects using switchgrass are producing better yields, but have not yet reached large scale deployment. There is, moreover, much experience with designing and operating production, transportation and storage systems, as well as safely handling ethanol. Brazil, in particular, has a strong interest in this fuel since it is the world's largest ethanol producer. Its rapidly increased use in the United States is driven by large tax subsidies given to ethanol used in motor fuels.

Fuel Transportation:
Hydrogen offers many advantages that are indisputable. It unfortunately also has several physical and thermodynamic properties that lead to extremely difficult technical and economic problems for its transportation and storage. While these may not necessarily be "deal-killers" for widespread use of fuel cells in a hydrogen-based economy, solutions are not at all apparent at this time.

One important set of severely difficult problems arises from hydrogen's low volumetric energy content. As previously noted, its energy content on a volumetric basis is far lower than that of other gaseous or liquid fuels. This makes transporting it very far by pipeline problematical.   Experience with current industrial natural gas pipelines is limited to pressures of approximately 100 atmospheres, diameters of 120 centimeters and gas velocities of 30 kilometers per hour. Within these parameters a pipeline carrying gaseous hydrogen would deliver, at best, less than 33 percent of the energy capacity it would have if it were transporting natural gas. If the pipeline carried liquid hydrogen, which also has a very low density, the disparity remains high in comparison with one carrying a liquid such as gasoline, propane or methanol. The pipeline for liquid hydrogen, moreover, would have to operate at approximately -240 degrees C, raising issues of brittleness and insulation as well as the design and operation of flanges, gaskets and pumps, meters and safety devices.

One must, however, evaluate the pipeline situation based on the same energy delivery rather than on the same volumetric delivery, i.e., a flow of three times as much hydrogen as natural gas. As a reasonable approximation, this will lead to pressure drops that might be 15 percent higher, and compressor power requirements, and hence operating costs that, because of the higher flow rate, are approximately 3.5 times higher. Hydrogen however also has a very low viscosity, which reduces pressure drop losses somewhat

when compared to other fuels moving at the same velocities. The low viscosity, however, also leads to problems with leakage through very small openings in flanges, gaskets and holes in pipes and equipment.

Given the technical and cost issues associated with pipeline-transportation of hydrogen, it appears more likely that it will always be generated locally, either in small distributed plants serving a limited geographic area, or within the fuel cell assemblies themselves.

Fuel Storage:
An assessment of storage possibilities must consider several technical issues, in addition to economic factors. They are:
- The total system weight and volume
- Discharge rates
- Recharging time
- Heating / Cooling requirements
- Operating temperatures and pressures
- Chemical stability

Hydrogen is widely distributed in high pressure cylinders, typically containing 850 to 8,500 normal liters at pressures of 135 to 205 atmospheres. Actual fuel cell systems that provide two kilowatts for telecommunication systems backup systems from one vendor[20] use a single standard 8500 liter gas cylinder of industrial grade[21] hydrogen that is reportedly adequate for 24 hours of use, and can be refilled for approximately $9.00. Polymer-lined carbon fiber composite storage cylinders have been certified and are commercially available for use and transport at pressures of 340 and 690 atmospheres. Cylindrical high pressure storage tanks are easily integrated into stationary systems. It would be difficult, although not impossible, to have them conform to other shapes, such as automobile gasoline tanks, for transportation use.

As another alternate storage technology, hydrogen may be reversibly converted to certain metal hydrides by simply contacting the metals and hydrogen at pressures of approximately 1 to 10 atmospheres and ambient temperatures. Examples are $LaNi_5H_6$, $NaAlH_4$, $LiNH_2$ and LiH. The bound hydrogen is then released by either increasing the temperature somewhat or reducing the pressure.

Several hurdles must be overcome before metal hydrides become more widely used. Firstly, the chemical reactions that form the hydrides release large amounts of heat. Typically 430,000 kilocalories per hour need to be dissipated for recharging a metal hydride at a rate of 1.67 kilograms of hydrogen per minute; this is a substantial cooling load. Secondly, the weight of the metal hydride per unit of hydrogen that will be available during the recovery stage is too high to be practical for many situations, particularly for automotive use. The U.S. Department of Energy has established a target of at least 6.0 weight percent hydrogen for the overall system, including tanks, piping, safety systems, etc., i.e., not narrowly limited to the metal hydride. Values of

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[20] havePower Inc., 1516 PE Street, Washington, DC 20005, USA
[21] Compressed Gas Association, CGA Grade B (99.95 percent hydrogen)

approximately 4-5 percent are currently being attained in actual applications. The amount of hydrogen stored can, however, be increased by using higher pressures, although additional costs for equipment and compression will be incurred. Alternately, lower temperatures may be used, but the rates of formation and dissociation become too low to be practical.

Many metal hydrides, moreover, are sensitive to carbon monoxide; one vendor[22] specifies a limit of 5 ppm CO. Finally, metal hydride systems that are currently available have not yet demonstrated an ability to perform after any more than ~1000 charge/discharge cycles under commercial or industrial conditions. This may be acceptable for many applications, but appears to rule out automotive uses. Metal hydride storage systems have, nevertheless, been found to be technically and economically acceptable for some stationary applications and are being marketed by several vendors[23] or incorporated in fuel cell systems.

Still another method to deliver and store hydrogen is to use it to produce a chemical compound that may be readily transported and decomposed upon demand to release its chemically bound hydrogen. One example of such a compound is sodium borohydride ($NaBH_4$.) When its hydrogen is needed, water is added, leading to a reaction, in the presence of a catalyst, that produces hydrogen and sodium borate. The chemical reaction is:

$$NaBH_4 \text{ (aq)} + 2H_2O \rightarrow 4H_2 + NaBO_2 + Heat$$
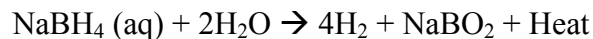
This technology has been demonstrated, with a storage capacity of approximately 4.0 weight percent hydrogen for the overall system, and is now commercially available.[24] Many other compounds are being studied for this approach. It is however not generally practical to regenerate these systems on a small scale or onboard vehicles.

Hydrogen may, of course, also be provided as a liquid at cryogenic temperatures. While this may be the lowest cost storage method, the liquefaction process consumes approximately 40 percent of the energy in the starting gas; this generally leads to an economically untenable situation.

Although methanol is an attractive fuel from a transportation and storage viewpoint, it is not problem-free. Methanol, as previously indicated, is moderately corrosive and is toxic.

The costs and storage capacities of the major current contenders are summarized on Figure 5.

Other potential hydrogen storage technologies that are being intensively investigated include the use of clathrates, carbon nanotubes and nanofibers, zeolites and glass microspheres. Breakthroughs are certainly possible, but do not appear to be probable in the near future. Assuming that a technical breakthrough does in fact occur, it will need to

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[22] Voller Energy Group PLC, Hamphire, United Kingdom
[23] Palcan Power Systems Inc, Burnaby, B.C., Canada; Energy Conversion Devices, Troy, MI, USA
[24] Millennium Cell, Inc., Eatontown, NJ, USA

Figure 5
Hydrogen Storage Capacity vs. System Cost
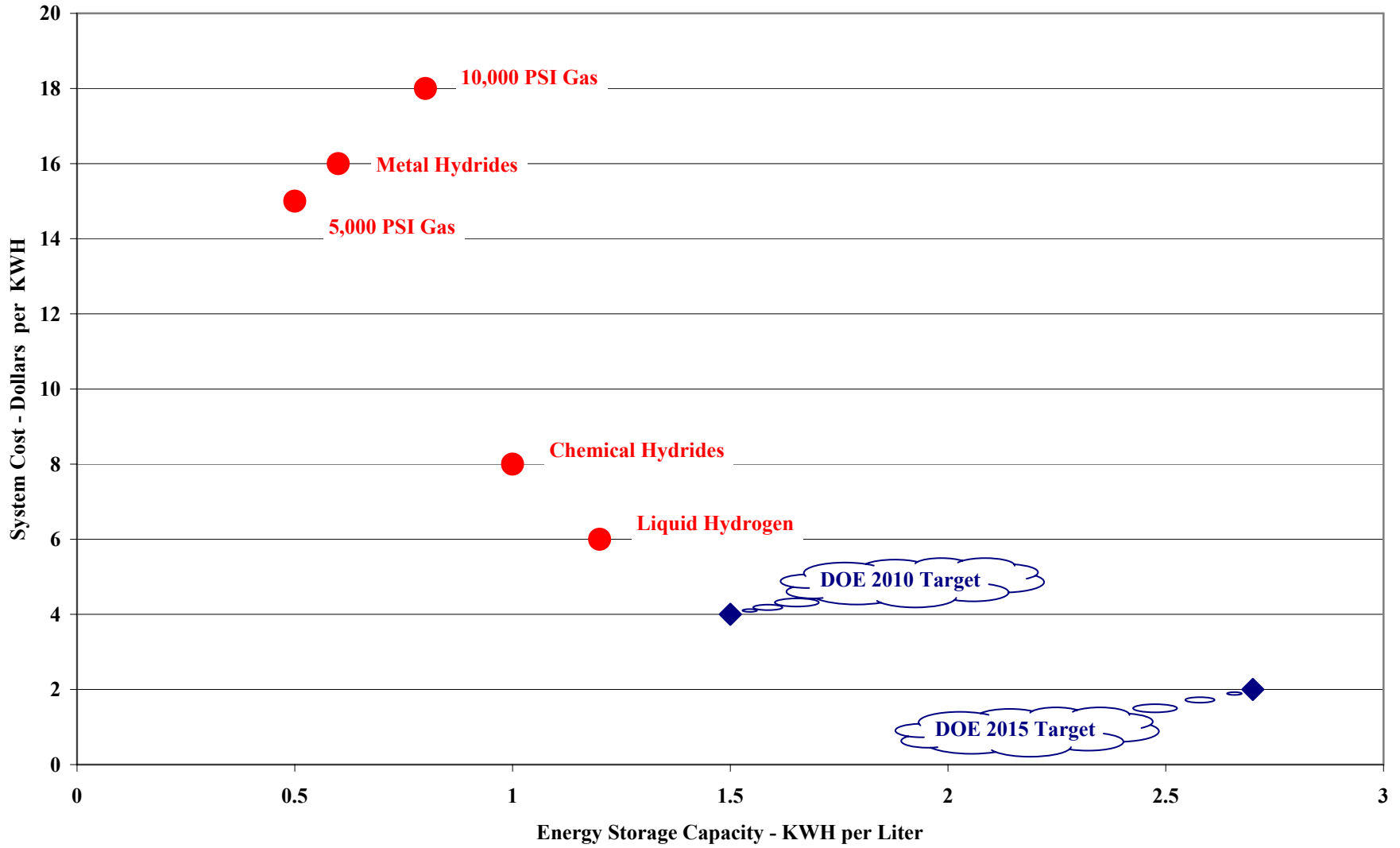
lead to an economically acceptable situation which will require cost-effective materials and implementation of efficient production systems. The challenges are huge.

The Oxidant:
In practical fuel cells, oxygen is most often used, although carbon dioxide is used in the MCFC. The oxygen may be supplied in pure form or as contained in ambient air. Hydrogen peroxide offers some advantages and so is occasionally proposed. It was, in fact, used by the U.S. navy in an experimental midget submarine in 1957. After an explosion, the navy concluded its use was too dangerous and lost interest.

Technical Matters – Fuel Cell Systems

The Fuel Cells
All fuel cells contain five basic parts, as shown on Figure 6. These are:
- a positively charged anode where electrons are produced
- a negatively charged cathode that accepts electrons to complete an electric circuit
- an electrolyte that allows movement of ions, but not electrons
- a cathode-side flow channel plate that delivers oxygen (or air) to the electrolyte
- an anode-side flow channel plate that delivers hydrogen to the electrolyte

These will be discussed in turn.

Electrodes: A fuel cell is superficially much like a battery, consisting of a casing that contains two electrodes separated by an electrolyte. It differs in that the electrode material in batteries is consumed or significantly altered by the chemical reactions that produce electricity and ultimately must be discarded or restored to their original composition by recharging. The fuel used in a battery is thus the electrode material such as lead in lead-acid batteries, the nickel and cadmium in NiCad batteries, the lithium in lithium-ion batteries, etc.
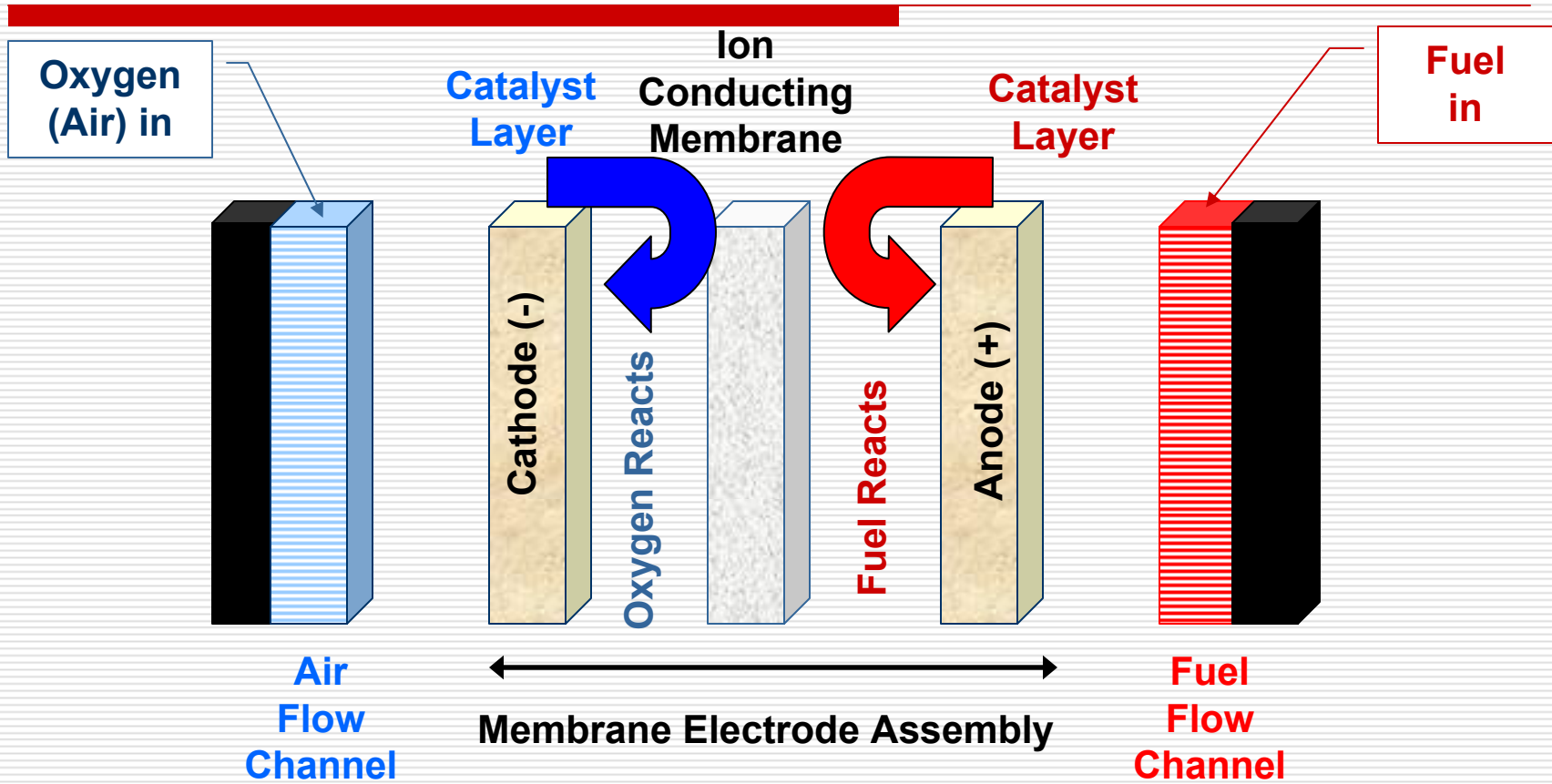
Conversely, the electrodes in a fuel cell are not consumed in the reactions; they primarily transport electrons that are released at the anode. Their construction is also more complex that those for batteries. They are generally either porous or contain channels enabling the gaseous fuel at the anode and the air at the cathode to diffuse through them, then through a porous catalyst film or plate where the chemical reactions take place, to finally contact the electrolyte. A very thin layer of the catalyst is most often supported on a carbon black substrate that tends to corrode, leading to the catalyst dislodging, aggregating and becoming less effective. Research is ongoing on other ways to include catalysts in MEAs, such as attaching platinum to carbon nonotubes.[25]

Much research is also underway to improve the performance of electrodes. A promising example is the use of a liquid tin anode in a SOFC. This allows direct use of plastics, heavy hydrocarbons and JP-8 as fuels without reformers, and a tolerance to sulfur-bearing contaminants.[26]

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[25] Pacific Fuel Cell Corp., Tustin, CA, USA
[26] CellTech Power, Westborough, MA, USA

Figure 6
Fuel Cell Components

Oxygen (Air) in

Catalyst Layer

Ion Conducting Membrane

Catalyst Layer

Fuel in

Cathode (-)

Oxygen Reacts

Fuel Reacts

Anode (+)

Air Flow Channel

Membrane Electrode Assembly

Fuel Flow Channel

A fuel cell using hydrogen, with liquid water as the product, has a theoretical voltage of 1.229 volts at 25 degrees C; if gaseous water vapor is the product, the theoretical voltage is 1.18 volts. The theoretical voltage falls as the temperature increases and the actual voltage of an operating cell, at all temperatures, falls as the current increases. A typical value is therefore closer to 0.7 volts. As with batteries, the higher voltages needed for many applications may be produced by stacking many basic individual MEAs in series. The cell's capacity to deliver electricity is determined by the electrode area. Thus higher output may be obtained by using larger electrodes or by connecting cells in parallel.

Electrolytes: The chemical reactions in a fuel cell release the fuel's electrons at the anode leading to the useful electric current. They simultaneously produce negatively charged ions that must flow to the cathode for oxidation to water and/or carbon dioxide. The material through which they flow, generally referred to as the "electrolyte", must be conductive and chemically stable at the operating temperature. It may be a liquid, an appropriate plastic membrane (generally termed a "Polymer Electrolyte Membrane," or PEM,) or a ceramic that contains appropriate metallic compounds. Practical membranes must be good proton conductors but must not conduct unreacted fuel or electrons. They must also be capable of absorbing large amounts of water, be chemically resistant, and mechanically strong enough to be made in thin sections.

Geometries: These individual components are assembled to create a fuel cell, as shown on Figure 6, most often as assemblies of planar components. A unit of one cell (two electrodes and the electrolyte), termed a "Membrane Electrode Assembly" or MEA, typically has an overall thickness of two or three millimeters.   An appropriate number of these, together with air channels, fuel channels, possibly coolant channels, electrical interconnects and end plates, are arranged in a stack to yield the desired voltage. Glass or compressed ceramics are used for sealing the components. The components may also be arranged within a solid block matrix, offering a rather similar geometry

Alternately, the membrane electrode assemblies can be arranged as round or flattened tubes. These are easier to seal, but must be thicker for structural and fabrication reasons, leading to a higher resistance to flow. Air and fuel flow paths are, conversely, easier to arrange than those in planar units. Several suppliers[27] of high temperature fuel cells are employing these geometries.

The overall fuel cell is rather complex structure, leading to durability problems and difficult manufacturing difficulties. Maintaining dimensions and flatness of planar components is difficult with today's manufacturing techniques. These can undoubtedly be overcome if and when production volume increases.

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[27] Acumentrics, Kyocera, Rolls-Royce, Siemens-Westinghouse

While all fuel cells are conceptually very similar, there are important differences in their construction, capabilities and limitations. The major types of fuel cells and their characteristics are as follow.

Low and Medium Temperature Fuel Cells
These units require either a pure hydrogen fuel or a fuel-processing unit that includes a reformer and purification equipment. The fuel cells produce low temperature waste heat, although some high temperature heat may be recovered from the exhaust gases of the fuel reformer if one is used.

Proton Exchange Membrane (PEM) Fuel Cells (PEMFC)
(Also called Polymer Electrolyte Membrane Fuel Cells)
PEM fuel cells use a solid polymer that can conduct hydrogen ions (H^+) from the anode to the cathode as the electrolyte, and electrodes that are typically porous carbon coated with a platinum catalyst. Any carbon monoxide in the hydrogen fuel gas must be removed since it poisons the platinum. A typical PEM sheet is 20 to 50 microns (1 business card) thick. Although many materials have been tried and used as PEMs, the best known is Nafion.[28] Much research is being directed to develop other membrane materials that have higher ionic conductivities, dimensional stabilities and lower costs.

These fuel cells operate at relatively low temperatures (~80 degrees C) which simplify their fabrication, reduce maintenance requirements and allow shorter warm-up times than PAFC, MCFC and SOFCs. Conversely, the low temperature exhaust gases can provide only low grade heat such as hot water. Small PEMFCs operate at atmospheric pressure; those larger than 1 KW usually operate at pressures of 2.5 to 3.50 atmospheres, and some at pressures of 10 atmospheres.

Proper water management is critical for the capacity and life of PEMFCs. The low humidity that is advantageous for removing the water that is formed must be balanced against the higher humidity that is necessary to keep the membrane from drying and cracking at the micro level.

Depending on the fuel and temperature, some PEMFCs can provide peak power within six seconds[29] of startup. Their relatively favorable power-to-weight ratio and insensitivity to orientation makes them a leading contender for transportation applications.

Alkaline Fuel Cells (AFC)
AFCs are the first ones that reached practical use. They employ a circulating alkaline solution, such as aqueous potassium hydroxide, as the electrolyte that carries hydroxyl ions (OH^-) from the cathode to the anode. Since carbon dioxide that is present in air,[30] and possibly also in the hydrogen fuel gas, reacts with the

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[28] Trademark and product of DuPont, polytetrafluoroethylene (PTFE), also known as "Teflon"
[29] Millennium Cell, Eatontown, NJ, USA
[30] Typically 370 ppmv

potassium hydroxide, it must be removed. This is readily accomplished and is a minor economic matter. Alternately, pure oxygen and pure hydrogen can be used. The electrodes are typically porous carbon coated with a non-precious metal catalyst. Newly developed AFCs operate at relatively low temperatures (25-70 degrees C) which simplifies their fabrication and reduces maintenance requirements, although at the cost of requiring increased amounts of catalyst. They have a relatively good power-to-weight ratio, making them a contender for transportation applications. This, together with their very high efficiencies (~60 percent,) has led to various military and space applications. Actual experience has shown stable operation for 8,000 hours, sufficient for many, but not all, applications.

Phosphoric Acid Fuel Cells (PAFC)

PAFCs were the first fuel cells to be applied to the 200^+ kilowatt applications. They use a porous silicon carbide matrix that contains pure liquid phosphoric acid that can conduct hydrogen ions (H^+) from the anode to the cathode as the electrolyte. The electrodes are typically porous carbon coated with a platinum catalyst. As with PEMFCs, carbon monoxide in the hydrogen fuel gas must be removed since it poisons the platinum at the operating temperatures. PAFCs operate at medium temperatures (~150-220 degrees C) which simplifies their fabrication and reduces maintenance requirements. They have a relatively good power-to-weight ratio but are sensitive to orientation, thus making them a poor contender for transportation applications. Their high efficiency, however, has led to various military applications.

The thermal output from PAFCs is at a sufficiently high temperature to be used in absorption chillers.

Direct Methanol Fuel Cells (DMFC)

Methanol may be used as a fuel by reforming it with steam to produce hydrogen. As generally used, however, the term "DMFC", however, refers to a fuel cell that uses liquid methanol directly, without reforming it. The fuel cell is a PEM type with membranes that can conduct hydrogen ions (H^+) from Pt/Ru alloy anodes to Pt cathodes,[31] and, depending on the amount of catalyst, operates at temperatures of 50-120 degrees C or, with more catalyst, at room temperature.

A major problem with DMFCs has been the undesirable flow of methanol from the anode through the electrolyte to the cathode (termed "methanol crossover") where it is oxidized, releasing heat. This phenomenon leads to wasted methanol and reduced output of electricity. Since this has often been a problem with Nafion membranes, other membrane materials such as poly-benzimidazole,[32] perfluorosulfonic acid,[33] polyphenylsulfonic acid,[34] polyvinylidenefluoride,[35] and

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[31] Much of the intellectual property and patents are owned by Direct Methanol Fuel Cell Corporation (Subsidiary of Viaspace), Altadena, CA, USA
[32] Plug Power, Latham, NY, USA
[33] DuPont, 3M

others are now being developed that appear capable of having 40 to 90 percent greater electrical outputs.[36]

These units are currently being sold as battery chargers and specialized remote applications. They are most likely to soon be used in small consumer products such as laptop computers and portable audio systems such as MP3 players.

High Temperature Fuel Cells
These units may use a wide variety of fuels, including carbon monoxide, since they operate at temperatures that are sufficiently high to internally reform many chemicals. The fuels may, however, require purification equipment to remove sulfur and possibly other impurities. These fuel cells also produce high temperature waste heat that can, in turn, produce high temperature/pressure steam that can then be used with a steam turbine to produce additional electricity (i.e., a bottoming- or combined-cycle.) The high temperatures, moreover, obviates the need for humidifying the air and/or fuel, and allow use of non-precious metals at the electrodes, somewhat reducing costs. Additionally, catalyst poisoning by carbon monoxide is not a problem, but poisoning by sulfur compounds is. Typically total sulfur (H_2S+COS) concentrations are limited to not exceeding $0.5 - 1.0$ ppmv. Recent work with other catalysts such as ceria[37] appears to offer the possibility of raising this limit to 500 ppmv.

Since the membrane-electrode-assembly consists of layers of materials with differing thermal conductivities and ductilities, long startup and shutdown times (up to 72 hours from cold start to standby[38]) are currently required to reduce damage by thermal shock. Their high-temperature operation also leads to problems caused by corrosion, sealing problems within the cells and stacks, and complex manufacturing techniques. Although these are the most efficient units, their complexity, space requirements and high temperatures virtually rule out their applicability to the non-military transportation market. These disadvantages are, however, partially offset by allowing the use of inexpensive cell materials and catalysts.

> **Molten Carbonate Fuel Cells (MCFC)**
> MCFCs operate at 600-700 degrees C, utilizing a ceramic[39] matrix that contains a molten carbonates[40] as the electrolyte to carry carbonate ions (CO_3^{-2}) from the cathode to the anode. Nickel is used as the catalyst. The CO_2 is the oxidant. Actual experience has shown that electrical output and efficiency decrease with time and, for economic reasons, cell components must be replaced approximately every three years. This is a very costly problem.

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[34] T/J Technologies
[35] Arkema (formerly Atofina Chemicals, Inc.)
[36] Gas Technology Institute; Toray Industries
[37] Franklin Fuel Cells, Malvern, PA, USA
[38] FuelCell Energy Corp., Danbury, CT, USA
[39] Typically $LiAlO_2$
[40] Typically Na_2CO_3, K_2CO_3, La_2CO_3

Solid Oxide Fuel Cells (SOFC)
SOFCs can operate at the highest temperatures, ~1000 degrees C, used for fuel cells, producing the highest efficiencies. They typically use a solid nonporous matrix of yttria-stabilized zirconia as the electrolyte that carries oxygen ions (O^{-2}) from the cathode to the anode. Ceria-gadolinium-oxides are also used since they can operate effectively below 700 degrees C, leading to fabrication and durability advantages. The air electrode is commonly a perovskite[41] such as Lanthanum-Strontium-Magnetite (LSM) or a Ni/YSM cermet. One vendor[42] provides anodes and cathodes that are each 50 microns thick each and a Zr-based electrolyte that is 120 to 150 microns thick. A membrane electrode assembly can therefore have a thickness of 220 to 250 microns.

Typical efficiencies of the major types of fuel cell systems are summarized in Table 3.
Table 3

Type	Operating Temp. C	Efficiency[43] Percent	Practical Thermal Output
Low Temperature Units			
Proton Exchange Membrane	50-100	40 – 47	Warm water
Alkaline	90	50 – 60	Warm water
Phosphoric Acid	150-220	~35	Hot water
Direct Methanol	50-100	25 - 40	Warm water
High Temperature Units			
Molten Carbonate	600-700	~55 70% in Combined Cycle[44] mode	Steam
Solid Oxide	650-1000	45 – 50 80% in Combined Cycle mode	Steam
The Competition			
Heavy Duty Truck Engine		45	
Gas Turbine Comb. Cycle		54	
Diesel Engine Power Plant		52	

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[41] An oxide with a structure similar to that of $CaTiO_3$, frequently expressed as ABO_3
[42] Nextec Materials Ltd., Lewis Center, OH, USA
[43] Based on electrical output only, HHV basis
[44] additional power is attained from the fuel cell system by recovering otherwise wasted heat through stream production and using this in a steam-turbine-driven generator.

Fuel Cell Catalysts: Today's fuel cells use oxygen (or carbon dioxide in MCFCs) as the oxidant at one electrode and either hydrogen or carbon monoxide as the reactants at the other electrode. The rates of chemical reaction, however, are too slow, particularly at the cathode,[45] to be useful at ambient temperatures, and are therefore increased by operating at substantially higher temperatures or using catalysts. The most common catalyst is platinum, which, in addition to being very expensive, is poisoned by carbon monoxide at low temperatures. Sources of platinum cause another concern. As seen on Figure 7, only 4.1 percent originates in North America. Interruptions of supplies from other countries and regions can arise from many easily imagined and realistic scenarios.

As side but important, issues, it is noted that South African ores contain only 4 to 7 grams of platinum group metals[46] per ton of ore. Thus, in addition to pure platinum the recovery processes also produce large amounts of solid wastes; allowing for refining losses this is 7 to 12 tons of ore per gram of platinum produced. Additionally, platinum smelting and refining are carried out in large electric furnaces at temperatures of 1,350 to 1,600 degrees C; this is an energy intensive process.

The reaction rates at the higher temperatures encountered in MCFCs and SOFCs allow lower cost materials such as nickel to be used as electrochemical catalysts

Operating Temperatures and Thermal management: Thermodynamic considerations indicate that fuel cells will produce their highest voltages at low temperatures. Since, conversely, rates of chemical reactions, and hence electron production, and the conductivity of protons through membranes increase with temperature, fuel cell capacity is, in practice, favored by operation at high temperatures.

The heat released by the oxidation process is easily dissipated in small fuel cells by natural convection. In larger units it is transferred to cooling air, cooling water, or to fuel that is passed through separate passages in the fuel and/or air distribution plates. This, of course, complicates the design and fabrication of the fuel cell stacks, requires additional equipment and incurs additional operating costs. Ultimately the heat of reaction is transferred to the incoming air and fuel, where it may provide the energy for internal reforming, or is wholly removed in the exhaust gases.

Low temperature operation, particularly in a sub-freezing environment, leads to two major problems. Since rates of chemical reaction and diffusion of gases through electrodes and of ions through electrolytes will initially be slow, startup at low temperatures is somewhat of a problem. It may take 5 to 10 seconds to reach 50 percent of rated power at -15 degrees C, but 90 to 100 seconds at -30 degrees C. Additionally, removal of the water formed during the chemical reactions is slower, and may even lead

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[45] The oxygen reduction reaction at the cathode is 100 times slower than the anode reaction, and therefore establishes the overall rate of electron production.
[46] Platinum, Palladium, Rhodium, Ruthenium, Iridium, Osmium

Figure 7
Platinum Sources
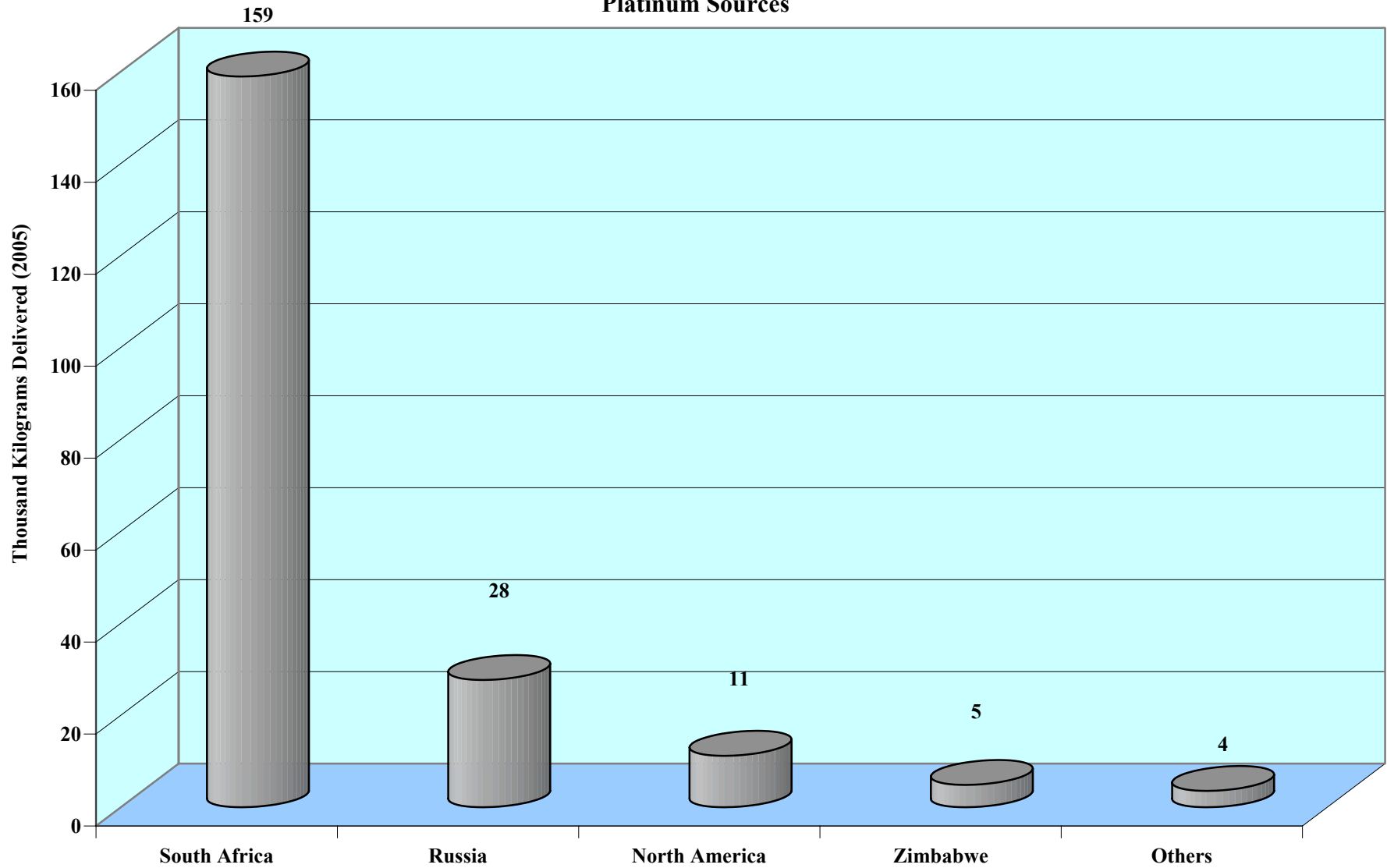
to freezing. Once a fuel cell is started, the heat of reaction is generally more than adequate to sustain operation.

Currently, many fuel cells can start and operate at ambient temperatures of -10 to +40 degrees C. This is acceptable for most, but not all, practical applications.

Operating Pressures: Thermodynamic considerations show that operating at elevated pressures will increase the theoretical energy that can be produced by a fuel cell for two reasons. Firstly, the voltage will increase, and secondly, the concentration of oxygen at the cathode catalyst surface will increase, leading to faster reaction rates.[47] Although high pressures will reduce the fuel cell's size for a given output, the overall system becomes more complex, sealing problems increase, the energy and economic penalty of air compression increases and, perhaps most importantly, reliability may suffer. Current practice is to operate fuel cells between atmospheric pressures and approximately 10 atmospheres.

Air Supply: Air must be forced into the internal passages of large fuel cell stacks by blowers or compressors. Smaller fuel cells such as those used for hand-held devices are able to rely entirely on diffusion through a porous cathode ("air-breathing".) Their pores, however, are susceptible to plugging by airborne particulate matter, by water in very humid environments, or by ice crystals in cold environments.

Water Management: Water forms from the hydrogen fuel at the cathodes of AFC, PEM, PAFC, and at the anode of MCFC and SOFC, and must be removed. Some membranes, however, require an adequate water concentration in order to conduct the protons to the anode from the cathode. Furthermore, micro cracking will occur if the membrane dries out, reducing its performance. The air supplied to larger fuel cells is therefore humidified (or dried) to an appropriate moisture level. Some fuel cell systems also require the fuel gas to be humidified.

The water that is formed during the oxidation process must also be removed. This may occur by simple diffusion through the porous cathodes of air-breathing fuel cells. Larger forced-air systems carry the water vapor out in the exhaust air stream. Depending on the application, the water may be condensed and recovered. Water removal from fuel cells operating at low temperatures is not a trivial matter; inadequate removal may lead to ice formation that will degrade performance, and may even lead to loss of all electrical output.

Technical Matters – Auxiliary Systems

Power Conditioning: All fuel cells generate direct current. Although this is useful for electronic devices that normally operate with batteries such as cell phones and a few other items such as variable speed drives, the vast majority of civilian uses require 50 or

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[47] Berning T. and N. Djilali, Three Dimensional Computational Analysis of Transport Phenomena in a PEM Fuel Cell – A Parametric Study, Journal of Power Sources 124, pp. 440-452, 2003

60 Hz alternating current. A complete system for many applications therefore requires a DC-to-AC voltage inverter. The use of fuel cells rather than batteries, however, does not introduce significant additional technical challenges.

Water Treatment: The water required for air and/or fuel humidification or to produce steam for reforming processes must not have impurities at the levels normally present in city, river or sea water. Purification equipment such as softeners or reverse osmosis units may therefore be necessary. Additionally, chemicals and delivery/dispersion equipment may be required for corrosion control of cooling water. These are well developed technologies, and their application to fuel cell systems does not introduce significant additional technical challenges.

Safety and design/fabrication/construction standards: Several broad concerns must be addressed when considering the use of fuel cells. They may be categorized as follows:

- ❑ Fuel production, storage and distribution: Fuel purity is more of an issue for fuel cells than encountered in other applications. New standards are therefore being prepared by organizations such as the ASTM covering the determination of various contaminants in hydrogen and related fuel cell feed gases. There is much successful experience with handling hydrogen and other chemicals in industrial settings, but relatively little in the individual consumer sector. A new section of the ASME Piping Code B31 is therefore being developed. *ASME B31.12, Hydrogen Piping and Pipelines*, will contain requirements for commercial and residential sectors, as well as for distribution, power, process and transportation applications. Fuel cell cartridges are currently not permitted on airplane passenger compartments, although they may be transported as cargo. The International Electrotechnical Commission (IEC) has now published safety specifications for small fuel cells and their cartridges, including those for methyl alcohol, formic acid, butane, hydrogen and sodium borohydride. It is expected that these standards will be accepted in various countries by early 2007.

- ❑ Fuel cell construction and performance: Test procedures for all components of fuel cell power systems are covered in ASME *PTC 50, Performance Test Code on Fuel Cell Power Systems.* ANSI/CSA America document *FC-1, Stationary Fuel Cell Power Standards* may also be consulted. Performance test procedures for automotive applications have been or are being developed by the Society of Automotive Engineers, including those covering *Fuel Cell Systems (SAE J 2615), Fuel Processor Subsystems (SAE J 2616), PEM Fuel Stack Subsystems (SAE J 2617) and Durability Testing of PEM Fuel Cell Stacks (SAE J 2722.) UL Standard 2265, Hand-held, Hand-transportable Fuel Cell Power Units with Fuel Containers* is under development.

- ❑ Fuel cell siting and installation: Guidance for indoor and outdoor installation, ventilation and fire protection for fuel cell systems is provided by the National

Fire Protection Association (NFPA) Document *NFPA 853 (2003) Installation of Stationary Fuel Cell Power Plants.*

❑ Electrical systems: The issues do not differ materially from those for other applications.

Barriers to market acceptance
Unclear benefits: As with most new technologies, the initial potential customers do not have a clear picture of many issues such as those associated with fuel, installation and safety, lifetimes and availability of replacement parts. Economic benefits may first be understood and accepted by those who make the purchase and then use the technology themselves, particularly in the industrial sector. The residential sector, however, has unique challenges. Landlords, for example, often simply pass along utility bills to tenants and see no self-benefit to investing in more efficient equipment. Conversely, in many cases the cost of utilities is included in rent or may be subsidized, so tenants see no self-interest in investing in energy conservation measures. Although environmental advantages may have some attraction, the experience in convincing customers to pay for them is not encouraging. For example, utility company programs that offer "green power" as an environmental benefit, but at a somewhat higher price, have not been spectacularly successful.

Capital costs: Capital costs of fuel cells are substantially higher than those of alternate electricity sources, typically being 5 to 10 times higher than those of a Diesel engine-generator or a combustion turbine-generator in the kilowatt size and 8 times as high as a boiler/steam-turbine plant in the 10 megawatt size. Their high costs arise in part from a current reliance on expensive components such as platinum catalysts and the proton exchange membranes.

Additionally, the market does not yet support large production runs that would lead to improved economies in purchasing and efficiently manufacturing to the close tolerances that are required. Planar systems, for example, require very close tolerances in edge and thickness dimensions, and gas diffusion and catalyst layers must be applied very uniformly. Current manufacturing processes, however, lead to poor yields of acceptable product. Improved production techniques are understood and can be implemented, but the required investments can not yet be economically justified.

Several parallel large markets will evolve in time. The first may be from suppliers of the end-use equipment such as cell phones, laptop computers or uninterruptible power systems that will incorporate them into their products. This group may elect to manufacture the fuel cells in-house, or subcontract production to a specialized manufacturer.

Operating costs: Fuel cell component lifetimes are shorter and replacement costs are higher than for those of other electricity generation systems. Stack life is only 3 to 5 years, and even these have not yet been demonstrated for SOFCs whose high efficiencies

offer the largest fuel cost savings. Durability problems will always arise from frequent startup/shutdown cycles encountered in applications such as automotive or residential electricity/heating generation units. The high temperatures required by SOFCs, however, exacerbate the difficulties of an already severe challenge.   Additionally, finding a use for or storing the thermal output when it is not needed for heating or cooling is certainly technically possible; doing so economically will be a major challenge.

The cost issue however has been reduced to acceptable levels for many situations. For example, there is a trend to using fuel cells to provide backup power to distributed telecommunication systems. Conventionally, the backup power has been provided by banks of batteries, which have high maintenance costs and are, in practice, completely replaced every few years. Life-cycle cost analysis, both with and without tax credits, have shown that the fuel cell option has approximately a 20 to 30 percent advantage over purchasing, installing and maintaining batteries.[48, 49]

No standard sizes: The vast market for batteries has developed, in large part, by the availability of standard sizes that can be readily found in stores throughout the world. The most common standard sizes (AA, AAA, C, D, 9-volt) are supplemented by standard button batteries used in calculators and electronic watches, as well as 5-10 miniature batteries used for very small devices such as hearing aids. It is estimated that 90 percent of portable battery-operated devices use AA, C or D standard batteries. The fuel cell industry does not yet, except for certain military applications, provide this convenience.

Inadequate fuel infrastructure for hydrogen and methanol: Although many chemicals are sold and distributed for industrial purposes, there is no mass market for hydrogen or methanol. Methane (as natural gas), LPG, gasoline, Diesel oil, jet fuels and coal are the only fuels for which a wide-scale infrastructure exists. Ethanol may join this group in the near future.

The lack of infrastructure is a particular problem for the much discussed automotive fuel cell applications. On-board fuel processing for automotive use is, for example, no longer being funded by the U.S. Department of Energy because it appears unlikely that the following criteria could be met by 2010.
- Low startup energy   <2MJ/50 KW(e)
- Rapid startup time   < 60 seconds to reach 90 percent of traction power
- Transient response   <5 seconds to accelerate from 10% to 90% power;
                           <5 seconds from 90% to 10% power
- Cost   <$65/KW(e)

A great many stationary applications do not face these constraints and are thus more likely to reach commercial acceptability in the foreseeable future.

Financing large fuel cell systems is difficult: Since there is very little experience with the design, construction and operation of fuel cell systems with capacities of even 1000

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[48] Smith, D., S. Rathod and J. Sanders, Switch Signals: Fuel Cells in Distributed Telecom Backup,
     Citigroup Global Markets, August 24, 2005, 56 p.
[49] Cellkraft AB, Stockholm, Sweden

kilowatts, the financial community believes there are major technical risks. Financing thus currently requires 100 percent equity; debt financing is simply not available. Virtually all systems in the 100^+ kilowatt size have depended on numerous grants for their viabilities. Related issues include difficulties in obtaining various types of insurance coverage, ranging from Fire to Business Interruption, at reasonable costs. The insurance companies also cite the lack of relevant experience with large projects as a concern.

Incentives for market acceptance

Fuel cell vendors and users are both benefiting from a number of governmental activities whose goals are to create or expand the market for fuel cells. These may be accomplished by either, or a combination of helping to:

❑ Facilitate fuel cell use by "early adopters"
❑ Reduce the direct price paid by purchasers (or to increase the direct price received by vendors)
❑ Reduce development and production costs of the fuel cells

Methods for implementing these will be discussed in turn.

Several multinational programs have been instituted to collect data and introduce fuel cells in real world, rather than laboratory settings. A major example is the Clean Urban Transport for Europe (CUTE) program, co-funded by the European Union. Started in 2001, 27 fuel cell-driven buses were operated in nine European cities, and supported by nine hydrogen production / refueling stations. Hydrogen was produced as follows.

Table 4

City	Hydrogen Source
Amsterdam, The Netherlands	On site electrolysis using "green energy"
Barcelona, Spain	On site electrolysis using grid energy and solar energy
Hamburg, Germany	On site electrolysis using wind energy
London, United Kingdom	Excess hydrogen from crude oil refining
City of Luxembourg	On site steam-methanol reforming
Madrid, Spain	Excess hydrogen from crude oil refining
Oporto, Portugal	Excess hydrogen from crude oil refining
Stockholm, Sweden	On site electrolysis using hydro energy
Stuttgart, Germany	On site steam-natural gas reforming

Iceland and Stockholm have indicated they believe the data obtained during the program's first two years is adequate, and the cost of continuing for a third year can not be justified by the additional information that might be obtained. They are therefore withdrawing from further participation; the remaining participants disagree and are continuing with the CUTE program.

The Hydrogen Highway: Several countries and States are developing *"Hydrogen Highways"* as an important step in facilitating development of a hydrogen-based

economy. This is a major undertaking, requiring proactive efforts and coordination of Local Zoning Boards, Fire Marshall Offices, Environmental Protection Agencies and others. Criteria within which a station will be accepted as a participant must be developed, and a thorough educational program must be instituted for station operators and the potential customers. Examples include the:

❑ *California Hydrogen Highway* (CaH2Net) program that has a goal of siting 150-200 hydrogen fuelling stations throughout the State; currently, 12 to 20 are actually in place. Funding is being provided by various equipment and automobile companies and not-for-profit organizations. The State of California is initially[50] providing $6,500,000 through December 31, 2006 to co-fund establishment of up to three stations and purchase of various hydrogen-fuelled vehicles.

❑ *Hydrogen Highway* connecting Victoria to Whistler, British Columbia, to be operational for the 2010 Winter Olympics. The goal is to establish seven "nodes" of fuelling stations to accelerate the transition to a practical commercially acceptable hydrogen economy. Substantial funding is being provided by the Canadian government, with additional contributions from BC Hydro and Methanex Corporation. This project is currently in the "Study Phase."

❑ *Hydrogen Highway, Swedish West Coast* connecting Oslo, Göteborg, Malmö and Köpenhamm. One advantage of this region is its availability of enough surplus hydrogen from petrochemical companies to drive approximately 50,000 fuel cell vehicles 9,500 miles each. This project is currently in the "Study Phase."

❑ *East Coast Highway* connecting Boston, MA and Washington, D.C. Major advantages of this region are its high concentration of drivers, and general acceptance of new concepts. There are currently only three automotive hydrogen stations generally along this corridor; one in Washington, D.C., one at Penn State University, and one at Albany, NY. This project is currently in the "Preliminary Discussion Phase."

In a related development, Hydrogen Link (Denmark), HyNor (Norway) and HyFuture (Sweden) formed the *Scandinavian Hydrogen Highway Partnership (SHHP)*, whose goal is to help make hydrogen commercially available from a network of refueling stations.

Importantly however, *"Hydrogen Highway"* is not synonymous with *"Fuel Cell Highway."* It is entirely possible that in the end the hydrogen will be more economically used in internal combustion engines than in fuel cells, or that electric battery or hybrid vehicles will prove to offer the best overall combination of technical, economical and environmental advantages.

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[50] California Senate Bill 76

Several governmental programs have been undertaken to reduce the price of fuel cells. The primary one is allowance of tax credits to purchasers. At the U.S. Federal level, for example, there is a tax credit of 30 percent of the purchase price for installing a qualified fuel cell (effective 1/1/06 to 12/31/07.)[51] This, and various state-level[52] incentive programs offer quite small benefits, typically $3.00 to $5.00 per watt, but with caps on capacity or payment that limit benefits to small percents of the total project cost; most tax credit plans are symbolic rather than economically meaningful.

Many State's Public Service Commissions have instituted *Renewable Portfolio Standards*, within which Utility Companies must produce or acquire certain fractions of the electrical energy they sell from renewable fuels such as solar energy or biofuels, and they have included fuel cells in this category. In addition to the stick, many States also offer their Utility Companies incentive carrots for using "renewable energy".

Connecticut, for example, considers fuel cells to be a renewable energy source and is insisting that electrical energy produced from fuel cells by Independent Power Producers be purchased by the State's Utility Companies for a specified premium above the wholesale rate. They, moreover, are now allowing utility companies to enter into long-term power purchase agreements.[53] The Utility Companies, in turn, are allowed to include any incremental costs in their rate-base.

Programs to reduce costs include financial assistance for research and development. Many governments, individually or in consortia, are providing funds for developing fuel cell components and complete systems. Examples of supranational efforts include those of the European Union and the Nordic Energy Research Program. The Canadian government has provided very meaningful support through its National Research Council – Institute for Fuel Cell Innovation (NRC-IFCI.) Within the United States, many initiatives are being supported by military programs such as those of the Defense Advanced Research Projects Agency (DARPA) and the Office of Naval Research. Civilian applications are supported by Department of Energy's programs such as the Solid State Energy Alliance (SECA.) National laboratories such as the Lawrence Livermore National Laboratory, Los Alamos National laboratory, National Renewable Energy Laboratory, Pacific Northwestern National Laboratory, and Sandia National Laboratory each have major efforts underway directed to fuel cell-related development.

Actual Current Applications

There are now more than 2,500 non-military fuel cells installed throughout the world. They provide primary or backup power to buildings such as hotels, office complexes and schools, as well as serving various other needs. Virtually all of these are highly subsidized or are testing/demonstration units.

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[51] Energy Policy Act of 2005:
[52] For comprehensive lists of incentives see www.FuelCells.org/Info/StateActivity.pdf, and
   http://www.eere.energy.gov/afdc/laws/epact_2005.html
[53] CT Clean Energy Fund, Class I Renewable Development Projects, PON CCEF-P100-RD2-001 (v3)

Many others, however, are now economically viable on their own. Applications that are currently viable without subsidies include the following.

Backup / Standby Power Systems: The telecommunications industry requires backup power systems for telecommunication or radio base stations in rural or remote areas. These may require 1 to 5 kilowatts of 24 or 48 volt DC, dependable starting and operating at temperatures between -30 and +45 degrees C, and with full-load operation for at least 24 hours and frequently longer. At least three companies[54] are successfully providing PEM fuel cells for telecommunication backup systems, using hydrogen from locally mounted cylinders as the fuel. The backup power systems currently use batteries to carry the load for the first minute or so until the fuel cell comes online. These batteries, however, can have much lower energy delivery capabilities that those in conventional battery systems. They, moreover, can be recharged by the fuel cell. If the response to a loss of power must be met much faster, ultracapacitors may be used.

Remote data collection: An interesting application is that of remote data acquisition. One company[55] is offering a 50 Watt, 12 volt methanol-fuelled remote power system. The vendor indicates that this can operate a digital video recorder "…for more than two weeks without requiring additional fuel and can also be used to charge other 12 volt equipment such as laptops and cell phones."

Another application concerns the need to have real-time knowledge of water levels in a system of reservoirs in South Africa so that water delivery and safety issues may be properly managed. PEM fuel cell-powered backup systems,[56] using hydrogen from locally mounted cylinders as the fuel, initially provided four months of operation for the telemetry equipment that serves this need, and now are used as the backup for the electric grid system.

Mobile Uses: Fuel cells are now being used for propulsion of fork lifts,[57] wheelchairs, golf carts and similar devices. One European company[58] is providing its motor homes with fuel cells for operating onboard devices such as television sets, refrigerators and lighting. Another company[59] is providing a luggage transportation unit, consisting of a combination of a 500 Watt PEM fuel cell and a battery, that can carry a 380 kilogram load.

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[54] CellKraft (Sweden,) Plug Power (USA,) ReliOn, Inc. (USA)
[55] Sandpiper Technologies, Manteca, California, USA
[56] Intelligent Energy Ltd, London, England
[57] General Motors of Canada, FedEx and Hydrogenics Power Systems
   (with $1.45 million grant from Canadian government)
[58] Hymer Mobil Homes
[59] PCR & CARDEC, Germany

Summary of Serious Issues

❑ The production of hydrogen from hydrocarbons, alcohols or water requires a large amount of energy. This may more than offset any increased efficiencies that fuel cells may offer.

❑ Compression or liquefaction of hydrogen requires large amounts of energy. This may also more than offset any increased efficiencies that fuel cells may offer.

❑ Efficiencies of fuel cell systems are currently not substantially higher than those of conventional electricity generation plants based on modern combustion turbines or diesel engines. The latter, moreover, can use lower grade fuels than can fuel cells. Major efficiencies may arise from high temperature solid oxide fuel cells, but many durability and fabrication problems will need to be overcome before this becomes an operational and economic reality.

❑ The environmental performance of fuel cells is excellent. They, however, rely on fuels that were produced in chemical plants that have noticeable emissions. Some approaches to reforming fuels rely on water that can not be recovered or recycled. This may be a serious issue in much of the world and in remote locations. Additionally, production of platinum for fuel cell catalysts or palladium for purification of hydrogen is energy-intensive, and also leads to large amounts of solid wastes.

❑ Progress is being made in reducing the amount of catalyst required in fuel cells, and in the use of lower cost materials instead of platinum. Most of today's fuel cells, however, use materials such as platinum that largely come from undependable or unstable locations. To some extent "energy security" is being obtained at the cost of "materials insecurity."

Dynalytics' Predictions

❑ Hydrogen-based fuel cells will soon become the preferred backup technology for power supplies where reliability is critical such as telecommunication stations and for remote sites where servicing and fuel replenishment is costly.

❑ Methanol-based fuel cells will soon be offered for small portable equipment such as laptop computers and MP3 players, for which long-duration power output is perceived by users as an important feature, and cost is a relatively minor consideration.

❑ Hydrogen- or methanol-based fuel cells will soon be commonly used as battery chargers at construction, camping and similar sites where electricity is not

readily available, generator noise is undesirable, convenience is valued, and cost is a relatively minor consideration.

❑ Multi-hundred kilowatt power plants will commonly employ solid oxide fuel cells for electricity production within the next ten years, on the strength of unsubsidized economics. This application is not faced with as low a capital cost constraint as other uses are. It, moreover, is also not faced with durability problems caused by frequent startup/shutdown cycles. Importantly, utility companies and departments have technical staffs that understand and provide proper operation and service.

❑ Trucks and buses used for intra-city use will increasingly be fitted with fuel cells for propulsion power, based largely on cost subsidies and localized environmental benefits. They can accommodate the size and weight of the fuel cell and fuel storage systems, can be refueled from a central facility, and often operate in cities where their low air emissions and low noise levels are valued.

❑ Passenger automobiles will not use fuel cells for propulsion power on a wide-spread unsubsidized basis in the foreseeable future. The thermodynamic energy penalties of producing, transporting and storing hydrogen present hurdles that can not be economically overcome. Use of other fuels does not appear to offer substantial benefits. It is certainly not yet clear that fuel cell-powered automobiles will be able to compete with electric battery or hybrid vehicles, which are also continuing to improve. It is, moreover, likely that society will respond to increasing fuel costs and environmental pressures by improving mass transportation systems.

❑ Fuel cells for residential production of combined heat and power require units that can withstand on-off cycles many times per day. Very durable fuel cells will thus be necessary, together with an adequate servicing infrastructure. The fuel cell system must also react to changes in the ratio of electricity to thermal output demanded throughout a day. This will require systems for the storage or distribution of the electrical and/or thermal energy when one or the other is in excess, or for supplemental firing of a boiler; the economic penalties may be severe. It appears that this application is many years away from fruition.

Abbreviations

Abbreviation	Definition
AC	Alternating Current
BTU	British Thermal Unit
C	Degrees Celsius
dBA	Decibels, "A" weighted
DC	Direct Current
DMFC	Direct Methanol Fuel Cell
F	Degrees Fahrenheit
HHV	Higher (Gross) Heating Value
Hr	Hour
Hz	Hertz
Km	Kilometer
L	Liter
MCFC	Molten Carbonate Fuel Cell
MEA	Membrane Electrode Assembly
NOx	Nitrogen Oxides
PAFC	Phosphoric Acid Fuel Cell
PEM	Proton Exchange Membrane
ppm	Parts per million
ppmv	Parts Per Million by Volume
psig	Pounds per Square Inch (Gauge)
SCF	Standard Cubic Foot
SOFC	Solid Oxide Fuel Cell

Conversion Factors

Multiply	By	To Get
Atmospheres	14.696	Pounds / Square Inch
Kilograms	2.2046	Pounds
Kilojoules	0.9471	British Thermal Units
Kilojoules	0.2387	Kilocalories
Kilometers	0.6214	Miles
Kilometers / Liter	2.3520	Miles / US Gallon
Kilowatt-Hours	859.184	Kilocalories
Kilowatt-Hours	3409.52	British Thermal Units
Kilowatts	859.184	Kilocalories / Hour
Kilowatts	1000	Watts
Liters	0.035315	Cubic Feet
Liters	0.2642	US Gallons
Normal Liters (of gas) [0 degrees C, 1 atmosphere]	0.03733	Standard Cubic Feet (of gas) [60 degrees F, 1 atmosphere]

Temperature: Degrees F = 1.8 x Degrees C + 32

THE AUTHOR

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