Cover Story

Fuel Cells, the Hydrogen Economy and You

Herbert W. Cooper
Dynalytics Corp.

Chemical engineers will play
an important role in the
development and deployment of fuel cells.
This primer summarizes some of the key
technical and economic issues
that must be overcome.

Fuel cells and hydrogen have the potential to reduce oil, gas and coal usage and improve the environment. Many companies, academic and government laboratories, and individual engineers are eager to participate in this rapidly developing field. However, it is not always clear which of the numerous activities required for the development, production and deployment of fuel cells and their fuels best match a particular party's abilities and goals. This article presents an overview of the current status and challenges of fuel cell development, and offers a few predictions. Companies may find this information useful in making investment decisions, and engineers in evaluating career possibilities.

Fuel cells have thermodynamic and environmental advantages over combustion-based processes for generating electricity. 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 imported crude oil. However, these are unlikely to occur for several decades.

Fuel cells do have a promising future, but because they offer other advantages — including high efficiencies, low emissions, high reliability, high energy density, quiet operation, and easy monitoring (see sidebar, p. 40).
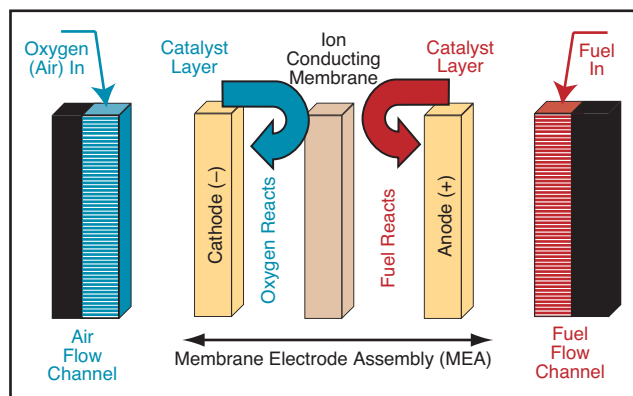
Fuel cell basics

All fuel cells contain five basic parts (Figure 1):
• a positively charged anode where electrons are produced
• a negatively charged cathode that accepts electrons to complete an electric circuit

This article is excerpted from a longer paper, which can be downloaded from the author's website, www.dynalytics.com, or www.aiche.org/cep

• 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.

While all fuel cells are conceptually very similar, there are important differences in their construction, capabilities and limitations. Table 1 summarizes some key characteristics of the major types of fuel cells.

Low- and medium-temperature fuel cells require either pure hydrogen fuel or a fuel-processing unit that includes a reformer and purification equipment. Their fabrication is simpler, maintenance requirements are less, and warm-up times are shorter than those of high-temperature fuel cells. The trade-off is that the low-temperature exhaust gases can provide only low-grade heat.

■ Figure 1. Basic components of a fuel cell.

High-temperature fuel cells may use a wide variety of fuels, including carbon monoxide, since they operate at temperatures high enough to internally reform many chemicals, although the fuels may require purification to remove sulfur and other impurities. The high-temperature waste heat can produce high-temperature/high-pressure steam for use with a steam turbine to produce additional electricity (*i.e.,* a bottoming or combined cycle).

Proton exchange membrane (PEM) fuel cells (PEMFCs). Any carbon monoxide in the hydrogen fuel gas must be removed or it will poison the PEMFC's platinum catalyst. The most common material for PEMs is polytetrafluoroethylene (PTFE), also known as Teflon or Nafion. Much research is being directed at developing other membrane materials that have higher ionic conductivities, dimensional stabilities and lower costs.

Proper water management is critical for maintaining 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.

Their relatively favorable power-to-weight ratio, their ability to provide peak power quickly, and their insensitivity to orientation make PEMFCs a leading contender for transportation applications.

Alkaline fuel cells (AFCs). These were the first fuel cells that reached practical use. Because carbon dioxide present in air (and possibly in the hydrogen fuel gas) reacts with the potassium hydroxide electrolyte, the CO_2 must be removed. This is readily accomplished and is a minor economic matter. Alternatively, pure oxygen and pure hydrogen can be used.

AFCs have a relatively good power-to-weight ratio, making them a contender for transportation applications. This, together with their very high efficiencies has led to various military and space applications.

Phosphoric acid fuel cells (PAFCs). The first fuel cells to be applied in applications of 200+ kW were PAFCs. As with PEMFCs, carbon monoxide in the hydrogen fuel gas must be removed since it poisons platinum. PAFCs have a relatively good power-to-weight ratio, but their sensitivity to orientation makes them a poor candidate for transportation applications. Their high efficiency, however, has led to various military applications.

Table 1. Characteristics of the major types of fuel cells.

Type	Operating Temperature, °C	Efficiency*	Practical Thermal Output	Electrolyte	Ion Movement	Electrodes and Catalyst
Low-Temperature						
Proton Exchange Membrane	50–100	40–47%	Warm water	Solid Polymer	H^+ from anode to cathode	Porous carbon coated w/ Pt catalyst
Alkaline	25–90	50–60%	Warm water	Alkaline Solution *e.g.,* KOH(aq)	OH^- from cathode to anode	Porous carbon coated w/ non-precious-metal catalyst
Phosphoric Acid	150–220	~35%	Hot water	Silicon-carbide matrix containing pure liquid H_3PO_4	H^+ from anode to cathode	Porous carbon coated w/ Pt catalyst
Direct Methanol	50–120	25–40%	Warm water	PEM	H^+ from anode to cathode	Anode = Pt/Ru Cathode = Pt
High-Temperature						
Molten Carbonate	600–700	~55% (CC 70%)	Steam	Ceramic matrix containing a molten carbonate	CO_3^{-2} from cathode to anode	Ni catalyst Anode = Ni or NiCr alloy Cathode = NiO doped w/ Li
Solid Oxide	650–1,000	45–50% (CC 80%)	Steam	Matrix of yttria-stabilized zirconia; or ceria-gadolinium oxides	O^{-2} from cathode to anode	Perovskite **

* Based on electrical output only, HHV basis. Additional power is attained by recovering otherwise wasted heat through steam production and using that in a steam-turbine-driven generator; CC = efficiency in combined-cycle mode.

** A perovskite is an oxide with a structure similar to that of $CaTiO_3$, frequently expressed as ABO_3. Common perovskites used as fuel cell electrodes are lanthanum-strontium-magnetite (LSM) or a Ni/YSM ceramic metallic composite.

Advantages of Fuel Cells

High efficiencies. When considering issues such as national or global energy and environmental matters, efficiency needs to be adjusted for the energy needed to produce, purify and distribute the fuel. These are substantial factors, particularly in the case of hydrogen. If the raw fuel is a hydrocarbon, the overall efficiency of the well-to-fuel-cell system might be 50–85% of that reported for the fuel cell system alone.

The efficiencies of most low-temperature fuel cell systems are not much better than the 45% typical of a heavy-duty diesel truck engine, and lower than the 52%–54% achieved by some large, modern gas-turbine combined-cycle or diesel-engine power plants. However, fuel cell efficiencies do not drop at part-load operation, but are maintained at all load points between 15% and 100% of rated output. The efficiency of a high-temperature fuel-cell-based power plant with a bottoming cycle for heat recovery may far exceed that of a gas-turbine or diesel-engine power plant.

Reduced air emissions. Virtually the only emissions from fuel cells are nitrogen oxides, carbon monoxide, carbon dioxide and water vapor, the exact amounts depending on the nature of the fuel and the type of fuel cell. Sulfur dioxide emissions will be virtually undetectable, since the fuel must be desulfurized before it enters a fuel cell.

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

Extremely high reliability. Unlike internal combustion engines and turbines, fuel cells have no moving parts. Like other generation technologies, however, their support systems often do rely on external components, such as pumps, blowers and fans, and on electronic components within control systems.

A PEM fuel cell system operating since April 2003 has successfully started up 1,106 times out of 1,111 attempts, a system availability of 99.5%. The availability of the fuel cell was 100% — failures arose in the balance-of-plant components.

Not all real-world experiences, however, have been positive. A comparison *(1)* of the performances of three fuel-cell-propelled buses and five diesel buses found that while the diesel buses attained 11,424 mi between propulsion-related service calls, the fuel-cell buses attained only 1,044 mi. More discouragingly, the fuel efficiency of the fuel-cell buses was 13% lower than that of the diesel buses on an energy basis, even without considering the energy needed for production and liquefaction of the hydrogen for the fuel cells. Obviously the situation will improve over time, but much needs to be accomplished.

High power density. As shown in the table, fuel cells have substantially higher energy-delivery capacities than batteries.

Technology	Specific Energy Delivery, W-h/kg
Lead-Acid Battery	30–50
Nickel-Cadmium Battery	45–80
Lithium-Ion Battery	110–160
Reusable Alkaline Battery	~ 80
Fuel Cell, Cylinder with 136 atm H_2	150
Fuel Cell, Cylinder with 680 atm H_2	700
Fuel Cell, Tank with Liquid Methanol	6,100

Quiet operation. Because they do not rely on the explosions that occur in diesel engines or have moving parts such as pistons or turbine shafts, fuel cells produce electricity extremely quietly. Simple fuel cell systems up to a few kilowatts typically emit noise levels of 35–53 dBA at 1 m; larger and more complex systems are noticeably noisier. Noise levels may be reduced, if necessary, with noise barriers, air inlet silencers and similar attenuators. (For comparison, relaxed speech is readily intelligible with a background noise level of 45 dBA.)

Quiet operation allows fuel cells that provide backup power to be operated within buildings, which is not practical for a diesel generator. Quiet operation is also beneficial for military applications such as "silent watch" and submarine propulsion.

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, 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 also be done for diesel engines, but cannot be done accurately for batteries.

1. Eudy, L., "VTA Prototype Fuel Cell Bus Evaluation: Interrim Results," National Renewable Energy Laboratory, Document No. NREL/PR-540-40012, presented at the American Public Transportation Association (APTA) Bus and Paratransit Conference, Anaheim, CA (May 2, 2006).

Direct methanol fuel cells (DMFCs). The term direct methanol fuel cell refers to a PEM fuel cell that uses liquid methanol directly, rather than reforming it with steam to produce hydrogen. Much of the intellectual property and patents for DMFCs are owned by Direct Methanol Fuel Cell Corp., a subsidiary of Viaspace (www.viaspace.com/dmfcc.php).

A major problem with DMFCs has been methanol crossover — *i.e.,* the undesirable flow of methanol from the anode through the electrolyte to the cathode, where it is oxidized and releases heat. This leads to wasted methanol and reduced electricity output. Since this has often been a problem with Nafion membranes, other materials are being developed.

Molten carbonate fuel cells (MCFCs). The MCFC's electrolyte is typically a $LiAlO_2$ ceramic matrix that contains a molten carbonate, such as Na_2CO_3, K_2CO_3, La_2CO_3. Carbon dioxide serves as 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 3 yr. This is a very costly drawback.

Solid oxide fuel cells. Operating at the highest temperatures, SOFCs have the highest efficiencies. Ceria-gadolinium oxides are sometimes used as the electrolyte because they can operate effectively below 700°C, which provides fabrication and durability advantages.

Technical issues — fuel cell systems

Electrodes. A fuel cell resembles a battery in that it consists of a casing that contains two electrodes separated by an electrolyte. Unlike a battery, though, a fuel cell's electrodes are not consumed in the chemical reactions that produce electricity— they primarily transport electrons that are released at the anode. Their construction is also more complex — 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. Typically, a very thin layer of the catalyst is supported on a carbon black substrate, which tends to corrode, causing the catalyst to dislodge, aggregate and become less effective. Research on other ways to incorporate catalysts, such as attaching platinum to carbon nanotubes, is ongoing.

Much research is also underway to improve the performance of electrodes. A promising example, being developed by CellTech Power (www.celltechpower.com), 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.

Electrolytes. Chemical reactions release the fuel's electrons at the anode to generate a useful electric current while simultaneously producing negatively charged ions that flow to the cathode for oxidation to water and/or carbon dioxide. The electrolyte through which the electrons and ions flow must be conductive and chemically stable at the operating temperature. It may be a liquid, an appropriate plastic membrane (a PEM), or a ceramic containing 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. The individual components are assembled to create a fuel cell, typically as assemblies of planar components. A unit of one cell, *i.e.,* two electrodes and the electrolyte, is called a membrane electrode assembly (MEA), and it typically has an overall thickness of 2–3 mm. An appropriate number of these, together with air channels, fuel channels, possibly coolant channels, electrical interconnections and end plates, are arranged in a stack to obtain the desired voltage.

Alternatively, the MEAs can be arranged as round or flattened tubes. These are easier to seal, but they must be thicker for structural and fabrication reasons, which creates a higher resistance to flow. Air and fuel flow paths are, conversely, easier to arrange than those in planar units. Several high-temperature fuel cells employ these geometries.

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. However, the reaction rates at ambient temperatures are too slow to be practical, so they are increased by operating at substantially higher temperatures or by 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 —only 4.1% originates in North America, leaving the fuel cell community vulnerable to supply interruptions.

Another consideration is that because South African ores contain only 4–7 g of platinum-group metals, the recovery process produces large amounts of solid wastes. Additionally, platinum smelting and refining are energy-intensive processes — carried out in large electric furnaces at temperatures of 1,350–1,600°C.

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.

Air and water. 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 handheld devices) can rely on "air-breathing" — *i.e.,* diffusion through a porous cathode. 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 that forms from the hydrogen fuel at the electrodes must be removed (although some membranes require an adequate water concentration in order to conduct the protons from the cathode to the anode). Furthermore, microcracking will occur if the membrane dries out, reducing its performance. Thus, the air supplied to larger fuel cells is humidified or dried to the appropriate moisture level. Some fuel cell systems also require the fuel gas to be humidified.

The water required for humidification or to produce steam for reforming processes must not contain impurities at the levels normally present in city, river or sea water, so purification equipment (*e.g.,* softeners or reverse osmosis units) may be necessary. Additionally, a chemical corrosion-control program may be required for the cooling water. These are well-developed technologies, and their application to fuel cell systems does not introduce significant additional technical challenges.

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. Water removal from fuel cells operating at low temperatures is not a trivial matter.
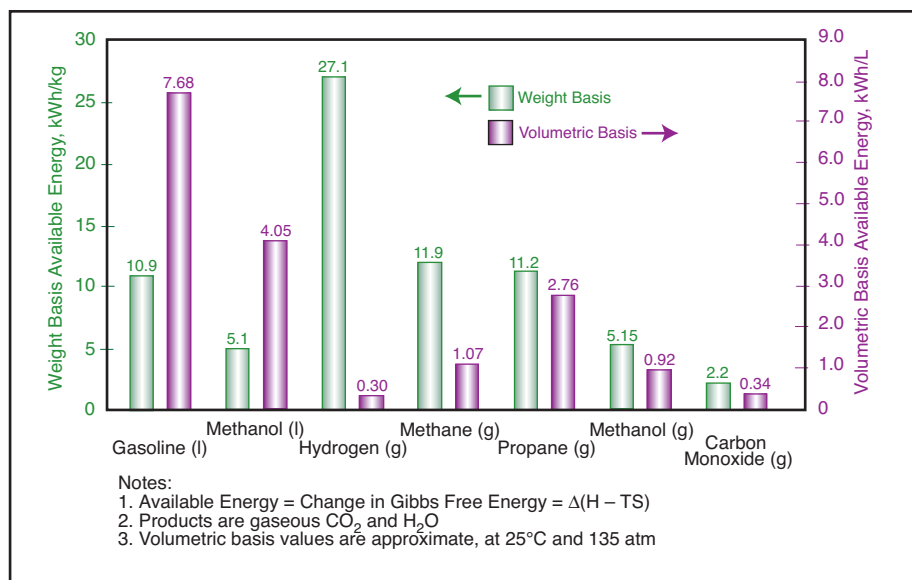
■ Figure 2. Electrical energy available from fuels on a weight basis and a volumetric basis.

Fuel production and purification

Today's fuel cells commonly use hydrogen as the fuel. Hydrogen has a very high energy density on a per-weight basis, but a very low one on a per-volume basis (Figure 2). Carbon monoxide may also be used as the fuel in very-high-temperature fuel cells.

The fuel may be produced directly within the fuel cell assembly (internal reforming). More commonly, raw fuels (*e.g.,* hydrocarbons, alcohols, ammonia) are converted to hydrogen or carbon monoxide (Figure 3). The processes involved may require more equipment and more-complex control systems than is readily apparent from this block diagram, and produce significant quantities of pollutants.

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 significantly smaller systems needed for many fuel cell applications. Researchers throughout the world are, there-fore, developing processes and equipment that are com-pact, durable, adequately efficient, and cost-effective for this application, such as miniature reforming and purifica-tion systems, improved catalysts and new approaches to heat integration.

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.

Electrolysis. Very pure (99.9999+%) hydrogen and byproduct oxygen may be produced from water by elec-trolysis. This relatively mature technology may fill a spe-cial niche in the production of electricity from fuel cells. The process 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 in locations where it cannot be economically transmitted to an electric grid.

The energy required for electrol-ysis may be reduced by operating at high temperatures. Development work at Idaho National Laboratory (www.inel.gov) and Cermatec, Inc. (www.cermatec.com) has demon-strated that electrolysis at 1,000°C provides total energy savings (including the energy required to produce the electricity) of approxi-mately 35% compared to 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 using thermochemical cycles. One promising technology is the iodine-sulfur (IS) process, in which sulfuric acid is decomposed at 800–1,000°C, producing water, sulfur dioxide and oxygen. The sulfur dioxide is then reacted with iodine and water at 120°C to produce hydrogen iodide (HI) and sulfuric acid that is recycled. Finally, the HI is dissociat-ed at 350°C to produce the desired hydrogen, plus iodine that is also recycled. There is virtually no net consumption of the sulfuric acid or iodine. This and similar thermochemical processes are being evaluated by several groups as adjuncts to nuclear reactors, which might be economical sources of the high-temperature thermal energy that is required.

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

Steam hydrocarbon reforming. Hydrocarbons, such as methane, propane, liquefied petroleum gas (LPG) and naph-tha, may be mixed with steam and passed over a catalyst, typically a nickel- or rhodium-based material. Hot combus-tion gases transfer heat to the reacting mixture, raising its temperature to approximately 700–850°C. Pressures of 3–27 atm are commonly used. The hot process stream leav-ing the reformer contains hydrogen, carbon monoxide, excess steam, byproduct carbon dioxide and unreacted methane. The thermal efficiencies of steam hydrocarbon reforming systems are typically between 75% and 80%,

depending on the composition of the hydrocarbon feed and the extent of heat recovery.

Partial oxidation. Alternatively, hydrocarbons may be partially oxidized by burning them with air or oxygen in quantities that are insufficient for complete combustion and with no or very little steam present. Although catalysts are not required, they are frequently used to increase the yield of hydrogen relative to carbon monoxide. Because the oxidation reaction is exothermic, no heat exchange equipment is needed, resulting in more-compact units. The thermal efficiencies of partial-oxidation reforming systems are typically between 70% and 75%, depending on the composition of the hydrocarbon feed and the extent of heat recovery.

Partial oxidation is attractive in areas where water is scarce since it uses little or no steam. The disadvantages of partial oxidation are 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, the purge gases from the purification sections have little use as a fuel, and the combustion air must be compressed to the oxidation reactor pressure.

Autothermal reforming. Another practical process consists of partial oxidation carried out immediately upstream of steam hydrocarbon reforming, the former providing the heat of reaction for the latter. This combination is a physically compact system, but it requires a larger downstream purification system.

Non-hydrocarbon fuels. In North America, much of Europe and Asia, coal is an attractive fuel from energy security and supply perspectives. However, its use brings many well-known disadvantages, including variable compositions, corrosive and catalyst-poisoning impurities, reliance on high-maintenance material-handling systems, and the dangers of coal mining. Additionally, its use generates greenhouse gas emissions (*i.e.,* CO_2) and other pollutants that are expensive to control.

Efforts to use coal follow two paths. One approach is to gasify the coal to produce carbon monoxide and hydrogen, which is the emphasis of the U. S. Dept. of Energy's (DOE) aggressive FutureGen program (www.fossil.energy.gov/programs/powersystems/).

The other is to use carbon directly in a fuel cell. Although this is potentially more efficient, it has all of the
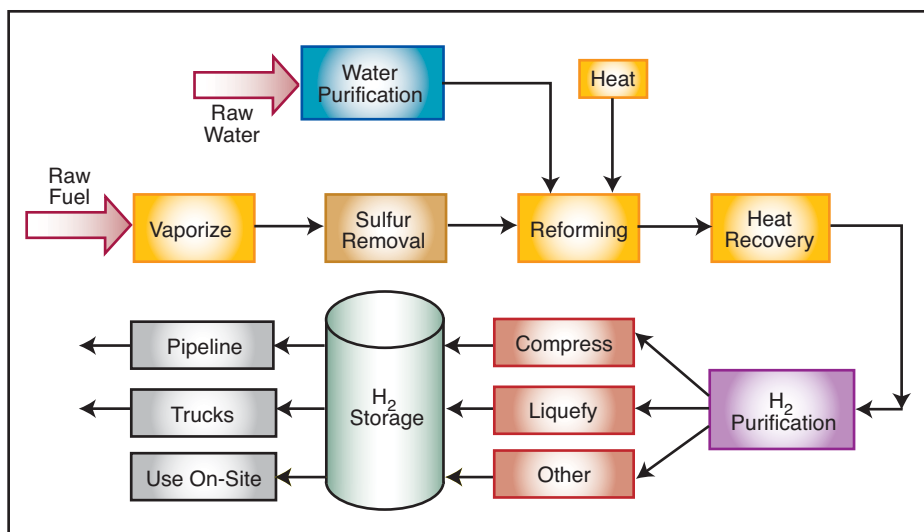
■ Figure 3. Hydrogen production and distribution.

mechanical problems of SOFCs, made even more difficult by the nature of coal. Many groups are developing this technology, but it is unlikely that practical systems will be available within the next 15 years.

Hydrogen may also be obtained by cracking ammonia, which is relatively easy to transport and store. This technology and its integration into operational fuel cells have been demonstrated by Apollo Energy Systems, Inc. (www.electricauto.com) and Argonne National Laboratory (www.anl.gov).

Fuel purification. Hydrogen purity is important for two reasons. First, reformer and fuel cell catalysts may be poisoned by compounds such as the sulfur-bearing odorizers in pipeline natural gas and commercial propane, as well as by carbon monoxide and unsaturated hydrocarbons. Other catalysts used to produce and purify hydrogen are also susceptible to poisoning, so fuel cell vendors typically limit the concentrations of alkali metals, ammonia, carbon monoxide, halogenated compounds, nitrogen, sulfur compounds, unsaturated hydrocarbons in the raw materials fed to their systems.

Impurities may be removed by numerous proven techniques, such as hydrodesulfurization, molecular sieves (zeolites), or reaction with zinc oxide, iron oxide or copper-impregnated adsorbents. Each has a niche, as well as capital and operating cost penalties. In practice, molecular sieves or semi-permeable palladium membranes that allow hydrogen to pass through while blocking other compounds are most often used within integrated fuel-cell systems. These can readily accept feeds with initial hydrogen contents of 25% or higher and produce a hydrogen product with a 99.999% purity.

Operating cost is the second important factor related to hydrogen purity. Unit costs of hydrogen in cylinders for

Table 2. Hydrogen cost depends on purity.	
Hydrogen Purity, vol.%	Unit Cost, $/scf
99.95	0.35
99.99	0.40
99.999	1.65
99.9995	1.75

Note: Typical mid-2007 costs. Actual costs depend on quantities, cylinder rental and other commercial arrangements.

small and mid-sized applications vary with purity (Table 2).

Although standards for hydrogen composition exist for uses ranging from general industrial applications (99.95% H_2) to semiconductor production (99.9997% H_2), compliance with these standards 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.

Hydrogen transportation and storage

Despite its indisputable advantages, hydrogen, unfortunately, also has several physical and thermodynamic properties that cause 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 apparent at this time.

Hydrogen's low volumetric energy content makes transporting it very far by pipeline problematic. Typical natural gas pipelines are limited to pressures of approximately 100 atm, diameters of 120 cm and gas velocities of 30 km/h. Such a pipeline carrying gaseous hydrogen would deliver, at best, less than 33% of the energy capacity of the same natural gas pipeline.

Similarly, a pipeline carrying liquid hydrogen would transport much less energy than one carrying gasoline, propane or methanol. The liquid hydrogen pipeline, moreover, would have to operate at approximately –240°C, raising issues of brittleness and insulation as well as the design and operation of flanges, gaskets, pumps, meters and safety devices.

Therefore, one must evaluate the pipeline alternative based on the same energy delivery rather than on the same volumetric delivery.

It appears more likely that hydrogen will always be generated locally, either in small distributed plants serving a limited geographic area or within the fuel cell assemblies themselves.

An assessment of storage possibilities must consider economic factors as well as the following technical issues: the total system weight and volume, discharge rates, recharging time, heating and cooling requirements, operating temperatures and pressures, and chemical stability.

Hydrogen is widely distributed in high-pressure cylinders, typically containing 850–8,500 normal liters (NL) at pressures of 135–205 atm. Cylindrical high-pressure storage tanks are easily integrated into stationary systems; however, it would be difficult (although not impossible) to make them in other shapes, such as automobile fuel tanks, for transportation use.

Another storage technology involves reversibly converting hydrogen to certain metal hydrides (*e.g.,* $LaNi_5H_6$, $NaAlH_4$, $LiNH_2$ and LiH) by simply contacting the metals and hydrogen at pressures of approximately 1–10 atm and ambient temperatures. 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. First, the chemical reactions that form the hydrides release large amounts of heat that must be dissipated. Second, metal hydrides are sensitive to carbon monoxide. Third, the weight of the metal hydride per unit of recoverable hydrogen is too high to be practical for many situations, particularly for automotive use. Finally, currently available metal hydride systems have not yet demonstrated an ability to perform after more than about a thousand charge/discharge cycles under commercial or industrial conditions. This may be adequate for many stationary applications, but it is not acceptable for automotive uses.

Another method to deliver and store hydrogen is to use it to produce a chemical compound that may be readily transported and then later decomposed upon demand to release its chemically bound hydrogen. One such compound is sodium borohydride ($NaBH_4$). When its hydrogen is needed, water is added in the presence of a catalyst and the resulting reaction produces hydrogen and sodium borate. The technology has been demonstrated, with a storage capacity of approximately 4.0%wt H_2 for the overall system, and is now commercially available. Many other compounds are being studied for this approach. It is, however, generally not practical to regenerate these systems on a small scale or onboard vehicles.

Liquid hydrogen at cryogenic temperatures represents a low-cost storage method, but the liquefaction process consumes approximately 40% of the energy in the starting gas. This is generally an economically untenable situation.

The costs and storage capacities of the major current contenders are summarized in Figure 4.

Other 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.

Other fuels

The technical and economic difficulties of producing and transporting hydrogen have led to searches for alternative fuels. The most promising candidate at this time is methanol, which may be reformed at relatively lower temperatures of 260–320°C, or may be used directly as a pure liquid or in dilute aqueous solution. As shown in Figure 2, liquid methanol has a reasonably high energy density on both a weight and volumetric basis. It is mostly produced from natural gas. Importantly, however, it has also been produced from coal.

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. Conversion efficiency, on an energy basis, is typically only about 70%, versus 85% for hydrogen production. On an overall basis, its production and use increases the total amount of hydrocarbons that would be used.

Methanol is moderately corrosive at ambient temperatures, requiring Grade 304 stainless steel storage tanks, piping, and wetted pump and valve components. It is also a toxic material that is soluble in water. Since chlorides and high-boiling-point compounds may lead to problems, a dedicated distribution system may be required.

Ethanol is another major fuel 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 corn and sugar cane. 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.

Barriers to market acceptance

Unclear benefits. Acceptance of fuel cells in the residential sector faces unique challenges. For example, landlords who pass along utility bills to tenants and tenants whose utilities are subsidized or included in their rent often have no interest in investing in energy conservation measures. Although environmental advantages may have some attraction, experience in convincing customers to pay for them is not encouraging — for instance, utility company programs that offer "green power" have not been spectacularly successful.

Capital costs. In part because fuel cells rely on expensive components, such as platinum catalysts and proton exchange membranes, their capital costs are substantially higher than those of alternative electricity sources, typically five to ten
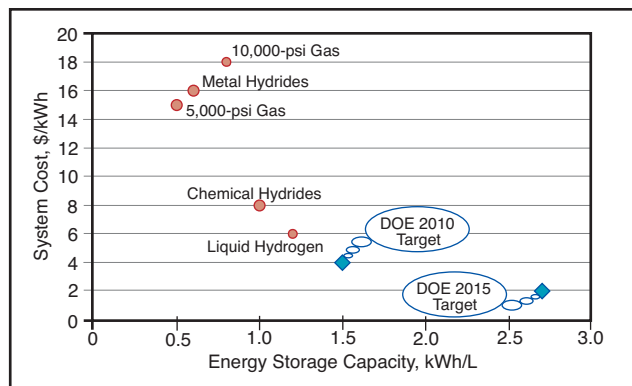
■ Figure 4. Hydrogen storage capacity vs. system cost.

times higher than those of a diesel generator or a combustion turbine generator in the kilowatt size range and eight times as high as a boiler/steam-turbine plant in the 10-MW size.

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. Improved production techniques are available, but the required investments cannot yet be economically justified.

Operating costs. Fuel cell component lifetimes are shorter and replacement costs are higher than those of other electricity generation systems. Stack life is only 3–5 yr, 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 start-up/shutdown cycles encountered in applications such as automotive or residential heating or electricity-generation units. 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.

Lack of 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 fuel cell industry does not yet, except for certain military applications, enjoy this convenience.

Inadequate fuel infrastructure. 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, jet fuels and coal are the only fuels for which a large-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. Stationary applications are more likely to reach commercial acceptability in the foreseeable future.

Financing difficulties. Since there is very little experi-

Actual Applications

There are now more than 2,500 non-military fuel cells installed throughout the world providing primary or backup power to buildings and serving various other needs. Virtually all of these are highly subsidized or are demonstration units. Many other applications are now economically viable on their own.

Backup/standby power systems. The telecommunications industry requires backup power systems for facilities in rural or remote areas. These may require 1–5 kW of 24-V or 48-V DC power, the ability to reliably start and operate at temperatures between –30°C and +45°C, and full-load operation capabilities of at least 24 h and frequently longer. Several companies [*e.g.,* CellKraft (www.cellkraft.se), Plug Power (www.plugpower.com), ReliOn, Inc. (www.relion-inc.com)] provide PEM fuel cells that use hydrogen from locally mounted cylinders for telecommunication backup systems. 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, but they 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. Sandpiper Technologies, Inc. (www.sandpipertech.com) offers a 50-W, 12-V methanol-fuelled remote power system that it says can operate a digital video recorder for more than two weeks without requiring additional fuel, as well as charge other 12-V equipment, such as laptops and cell phones.

In South Africa, real-time knowledge of water levels in a system of reservoirs is required so that water delivery and safety issues may be properly managed. PEMFC-powered backup systems using hydrogen from locally mounted cylinders initially powered the telemetry equipment that serves this need for four months. They are now used as the backup for the electric grid system.

Mobile uses. Fuel cells are now being used for propulsion of fork lifts, wheelchairs, golf carts and similar devices. In Europe, HYMER AG (www.hymer.com/eu/) manufactures motor homes with fuel cells for operating onboard devices such as television sets, refrigerators and lighting.

ence with the design, construction and operation of large fuel cell systems, the financial community believes there are major technical risks. It is also often difficult to obtain insurance coverage at reasonable costs.

Incentives for market acceptance

Vendors and users alike are benefiting from a variety of government activities aimed at creating or expanding the market for fuel cells. Federal and state tax credits (www.fuelcells.org/info/stateactivity.pdf and www.eere.energy.gov/afdc/laws/epact_2005.html) for purchasers of fuel cells could reduce the price paid by purchasers (or increase the price received by vendors), although most tax credit plans offer benefits that are a small fraction of the total project cost and are symbolic rather than economically meaningful. Many states offer utility companies incentives for investing in renewable energy.

Various programs provide financial assistance for research and development of fuel cell components and complete systems, such as the Canadian government's National Research Council – Institute for Fuel Cell Innovation (NRC-IFCI) and several national laboratories in the U.S., including Lawrence Livermore (www.llnl.gov), Los Alamos (www.lanl.gov), Pacific Northwest (www.pnl.gov), Sandia (www.sandia.gov), and the National Renewable Energy Laboratory (www.nrel.gov). The U.S. Dept. of Energy's Solid State Energy Conversion Alliance (SECA) also has major efforts underway directed at fuel cell development.

Several multinational programs have been instituted to collect data and introduce fuel cells in real-world (rather than laboratory) settings. For instance, the Clean Urban Transport for Europe (CUTE) program, which was co-funded by the European Union, was conducted between 2001 and 2006. It involved 27 fuel-cell-powered buses operating in nine European cities and supported by nine hydrogen production/refueling stations. Those stations used excess hydrogen from crude oil refining, or produced hydrogen via electrolysis using "green energy," grid energy, solar power, wind energy, hydro power, or steam-natural gas reforming.

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 agencies, and others, as well as thorough educational programs for station operators and the potential customers.

California's hydrogen highway (dubbed CaH2Net) currently has 24 hydrogen fuelling stations, and a goal of siting 150–200 stations throughout the state. The East Coast hydrogen highway connecting Boston, MA, and Washington, DC, is in the preliminary discussion phase. There are currently three automotive hydrogen stations along this corridor: one in Washington, DC, one at Penn State Univ., and one in Albany, NY. Major advantages in this region are the high concentration of drivers and general public acceptance of new concepts.

British Columbia and Sweden have projects in the study phase. The goal of the British Columbia hydrogen highway, which will connect Victoria to Whistler and is slated to be operational for the 2010 Winter Olympics, is to establish seven nodes of fuelling stations to accelerate the transition to a practical commercially acceptable hydrogen economy. The Swedish West Coast hydrogen highway linking Oslo, Göteborg, Malmö and Köpenhamm will benefit from surplus hydrogen from petrochemical companies — enough to drive approximately 50,000 fuel cell vehicles 9,500 mi each.

HyFuture (Sweden; www.hyfuture.eu/), Hydrogen Link

(Denmark; www.hydrogenlink.net/dk/hydrogenlink/eng/), and HyNor (Norway; /www.hynor.no/english) have formed the Scandinavian Hydrogen Highway Partnership (SHHP), the goal of which is to help make hydrogen commercially available from a network of refueling stations.

It is important to realize that "hydrogen highway" is not synonymous with "fuel cell highway." It is entirely possible that ultimately 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.

The more-serious issues

The production of hydrogen from hydrocarbons, alcohols or water requires a large amount of energy, as does the compression or liquefaction of hydrogen. This may 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. High-temperature SOFCs have higher efficiencies, but many durability and fabrication problems must be overcome before they become a reality.

The environmental performance of fuel cells is excellent; however, they rely on fuels that were produced in chemical plants that have noticeable emissions. Some approaches to reforming fuels rely on water that cannot be recovered or recycled, which 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 generates 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."

A few 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 SOFCs 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 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 powered by fuel cells, 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 widespread unsubsidized basis in the foreseeable future. The thermodynamic energy penalties of producing, transporting and storing hydrogen present hurdles that cannot 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.

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. **CEP**

HERBERT W. COOPER is president of Dynalytics Corp. (9 Sheffield Hill, Woodbury, NY 11797; Phone: (516) 921-7631; Fax: (516) 921-7632; E-mail: info@dynalytics.com), a company whose clients include government entities, major engineering firms, equipment vendors, oil and chemical companies, and aerospace firms throughout the world. He has over 40 years of experience with economic, technological and environmental aspects of power production, hydrogen production, steel mills, petrochemical production, oil refining, and similar industrial facilities. He received his bachelor's and master's in chemical engineering from the City College of New York, and a doctorate in engineering science (chemical engineering) from Columbia Univ. He is a member of AIChE, the New York Academy of Sciences, and the Société de Chemie Industrielle.