FUEL CELLS

by David P. Wilkinson

A major challenge facing mankind is to find much needed solutions to the increasing impact of energy consumption on the urban and global environment. Global warming and acidification of various fuel supply chains including fuel production and fuel use are major factors in the global impact. Greenhouse gas levels, particularly CO_2 (other greenhouse gases include H_2O, N_2O, CH_4 and O_3), have increased sharply since the beginning of the Industrial Era in the late 1700s. Significant increases are anticipated if the current trends continue and a commensurate rise in the global average temperature of between 1 to 4°C is expected in the 21st century. Developing countries such as China, with large coal reserves, can be expected to triple coal consumption in the next 20 years if power continues to be produced by coal burning. Motor vehicles, even lower emission gasoline vehicles, account for a major portion of greenhouse-gas production (at least 40% of U.S. emissions and over 25% of all global greenhouse gases). Global vehicle production in recent years is in the range of 58 to 65 million per annum.[1] Reserves of fossil fuels are large but finite, and there is growing evidence to suggest that the world production of crude oil will peak early in this century.[2] In the utility sector there are issues with the inflexibility and siting of central power generation, and the cost, power losses, and hazards of transmission grids. There is a current trend toward deregulation, distributed power and smaller power plants. Thus, new technology solutions are required to deal with global warming, global acidification, and other environmental pollution challenges, increasing vehicle numbers, power consumption and distribution, limitations and concentration of crude oil reserves, and long-term sustainability of energy supply.

Air Quality Issues

Global regulations related to fuel specifications and emission limits are becoming more stringent. For example, standards set for gasoline and diesel fuels include aromatics, olefins, benzene, lead, and sulfur (as high as 1,000 ppm today, down to 30 ppm in about 2006). Tailpipe air quality emission limits related to NMOG (non-methane organic gas), NO_x and CO are being set by various countries similar to those of the California Air Resources Board (CARB). Implementation schedules related to the type of emission vehicle [Transitional Low Emission Vehicle (TLEV), Low Emission Vehicle (LEV), Ultra-Low Emission Vehicle (ULEV), Super Ultra-Low Emission Vehicle (SULEV), and Zero Emission Vehicle (ZEV)] are in place, although this schedule is updated regularly to reflect technology status. As of the fall of 2000, CARB required 10% of cars sold in 2003 to meet the ZEV requirement (4% being true ZEV and 6% made up of equivalents). Today only battery and fuel cell powered vehicles can meet the ZEV requirements. A number of battery and hybrid battery electric vehicles are already on sale today but have issues such as limited range.

Fuel Cells: A Solution to Positive Climate Change

Increasing marginal costs and limits for further optimization of conventional technologies are driving new technology. Electrochemistry is playing a significant role in this technology change because of the inherent efficiency of electrochemical processes without the requirement of high temperature associated with the Carnot cycle for conver-

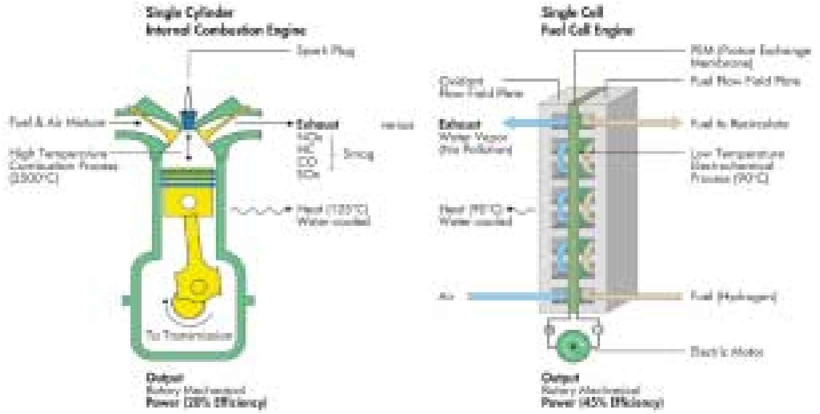


FIG. 1. Comparison of the internal combustion engine with a fuel cell engine.

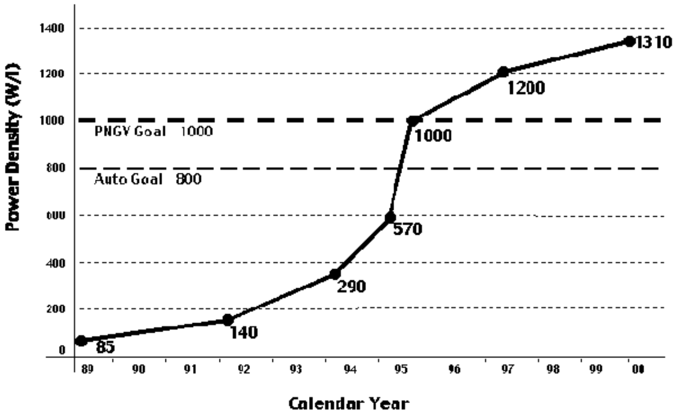


FIG. 2. Increase in fuel cell stack power density over the last decade at practical operating conditions.

An Electrochemical Solution to Global Climate Change in the 21st Century

sion of heat to mechanical energy. Fuel cells are an electrochemical device that will play a significant role in the strategy to effect positive climate change. Technical progress as well as investments in fuel cells for transportation, stationary, portable, and micro-applications has been substantial in recent years. A comparison of the internal combustion engine with a fuel cell engine is shown in Fig. 1. Of the five distinct types of fuel cells mainly determined by their electrolyte [Phosphoric Acid Fuel Cell (PAFC), Alkaline Fuel Cell (AFC), Polymer Electrolyte Membrane Fuel Cell (PEMFC) including the Direct Methanol Fuel Cell (DMFC), Molten Carbonate Fuel Cell (MCFC), and Solid Oxide Fuel Cell (SOFC)] the PEMFC is considered to be the fuel cell of choice for transportation applications, and, unlike the other fuel cell types, it has applicability in most market and application areas. The present view is very optimistic for fuel cell power generation and the status is presently in the pre-commercialization phase with extensive field trial testing. A number of demonstration programs are in progress worldwide, such as the California Fuel Cell Partnership, which involve OEMs, fuel providers, transit authorities, and state and government bodies.

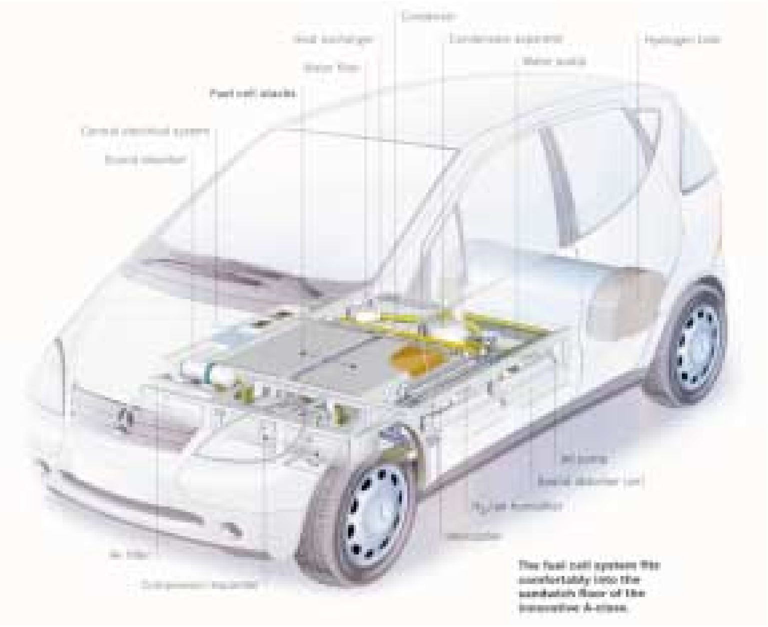


FIG. 3. Overall fuel cell system demonstrated in a DC A-class vehicle.

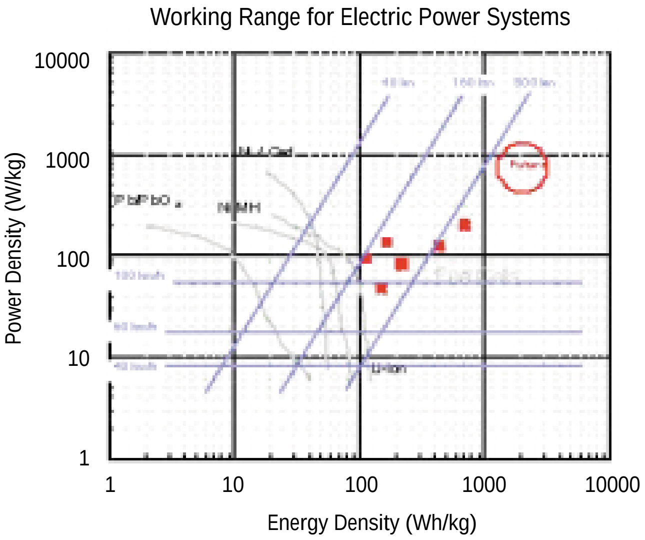
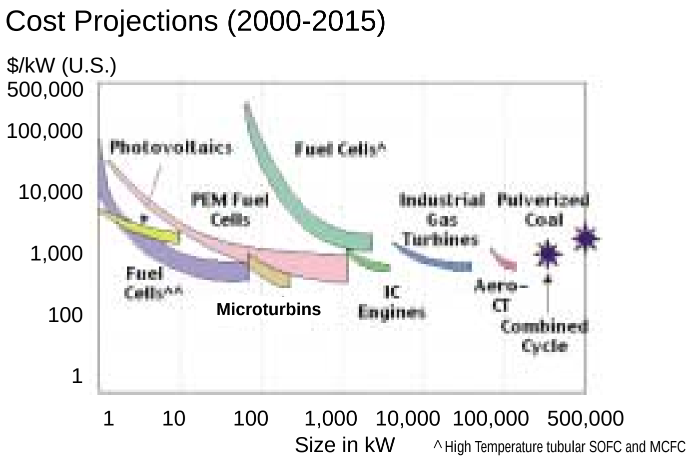


FIG. 4. Ragone plot for demonstrated battery and fuel cell systems.

Key milestones in the progress of fuel cells have been the demonstration of fuel cell stack and system power density, reliability, dynamic interface and response, cost potential, ability to operate on multiple fuels (fuel neutral), and field trial demonstrations in different applications. Transportation is perhaps the most challenging application because of the size constraints and the aggressive cost targets. Success here bodes well for other applications. An important early objective for the PEMFC was to demonstrate that the fuel cell stack could meet the various power density targets identified by the auto-makers, by the U.S. Department of Energy, and by the Partnership for a New Generation Vehicle (PNGV). Another important early objective was to demonstrate that the PEMFC stack and associated systems could operate under the dynamic conditions required for transportation and other applications. Both of these objectives were clearly demonstrated in the mid-1990s. Dramatic increases in fuel cell stack power density have been demonstrated over the last decade as shown in Fig. 2. The overall fuel cell system engine, including fuel cell stacks and fuel tank, can fit into the sandwich floor of small vehicles such as the A-class shown in Fig. 3. Dynamic operation has been demonstrated both in the lab and in field trials for different driving cycles with low and acceptable degradation. Non-hybrid fuel cell technology alone has reached a level that meets or exceeds targets identified by the automakers. Ragone plots such as shown in Fig. 4 indicate the clear advantage of fuel cell systems (includes tank and fuel) over battery systems in terms of range and energy density at a given power density. The trend for demonstrated hydrogen and methanol fuel cell vehicles (non-hybrid) is promising and shows that power densities and energy densities in the range of 1,000 W/kg and 1,000 Whr/kg, respectively, can be expected in the future. However, fuel cell/battery hybrids may offer some advantages with respect to cost reduction and reduced power density requirements, but can increase system complexity with the additional battery interface. These hybrids mainly consist of a fuel cell at variable load with batteries for short duration peak power (battery peaking) or a fuel cell at steady load with batteries at variable load (battery charging).

The priority for development and commercialization of the PEMFC has shifted from increasing power density to retaining it while improving reliability, cost reduction, and manufacturability. To succeed, fuel cells will eventually have to be competitive on an economic basis with the established and highly developed internal combustion engine for transportation applications, and conventional combined cycle and industrial gas turbine power generation. Cost reduction activities continue with the selection of low cost materials that do not compromise existing fuel cell performance and are consistent with the use of low cost, high volume, manufacturing processes. In addition, developing product designs that have inherent high yield and low scrap rates combined with eliminating components and parts in the fuel cell stack and system, and formation of supplier relationships to ensure manufacture of fuel cells in volumes that will result in sufficient economies of scale, all help to drive costs down. Cost projections, although challenging, are favorable for all fuel cell applications. For example, as shown in Fig. 5, stationary power system cost projections in the 2000 to 2015 time range[3] show smaller fuel cell power plants (< 2 megawatt) are cost competitive with larger conventional combined cycle power and industrial gas turbine power plants (> 5 megawatts).

Today, fuel cell operation on multiple fuels has been clearly demonstrated especially with respect to hydrogen, methanol, and natural gas. Hydrogen as a fuel is preferred because the overall fuel cell reaction has no direct emissions ($H_2 + 0.5O_2 \rightarrow H_2O$) and no known toxicity characteristics. If a renewable source of electricity is used for electrolysis, then a zero emission fuel cycle is achieved. This may be the only practical zero emission fuel cycle. Such renewable sources of power include hydroelectric, geothermal, wind power, biomass, and solar energy. Today, less than 2% of global power comes from such renewable sources. Hydrogen production from fossil fuels requires reforming options as shown in Fig. 6, and these are usually combined with some type of hydrogen clean-up option as shown in Fig. 7. Zero emission strategies for fossil fuels are possible based on conventional production technology or syngas production. For example, steam reforming of natural gas ($CH_4 + 2H_2O_{(g)} \rightarrow CO_2 + 4H_2$) or oxygen-blown goal gasification ($CH_{0.8}O_{0.08} + 0.46O_2 + H_2O_{(g)} \rightarrow CO_2 + 1.4H_2$), followed by CO_2/H_2 separation, which is capital and energy intensive,



(Source: Dan Rastler, Electric Power Research Institute)

FIG. 5. *Stationary power system cost projections in the 2000 to 2015 time range.*

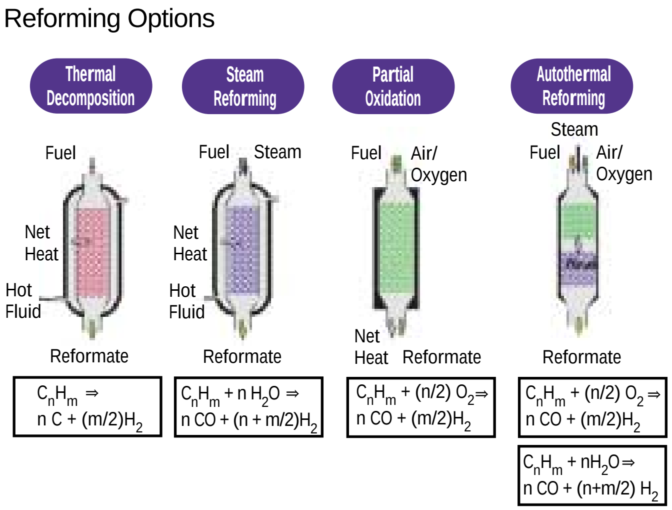


FIG. 6. *Reforming options for hydrogen production from fossil fuels.*

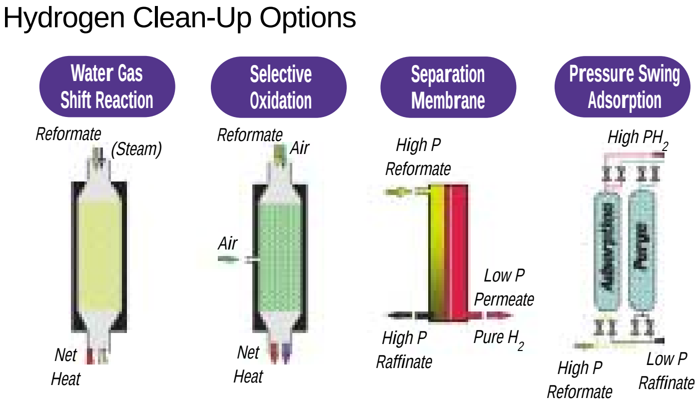


FIG. 7. *Hydrogen clean-up options for reformate from fossil fuels.*

and CO_2 disposal, which is costly. Some options for CO_2 disposal being investigated include depleted oil and natural gas fields, deep saline aquifers, deep ocean disposal, and deep beds of unminable coal.

Today, hydrogen as a compressed gas, liquid or metal hydride has issues with weight and low storage densities for onboard storage, and the sourcing and distribution infra-structure is not well developed. Figure 8 shows the energy density for storage of different hydrogen fuel sources. Other fuels are readily available today that are easier to handle and store (higher storage densities) and in many cases compatible with existing infra-structure. Methanol has excellent reforming characteristics but there are issues related to toxicity, flame luminosity, and corrosiveness. Gasoline and diesel have the least new infra-structure costs but require the highest temperature to reform, and have poor reforming characteristics relative to methanol, and the current sulfur content is too high. Fischer Tropsch liquids are less complicated compared with gasoline but have limited availability and high production costs for new facilities. Therefore, in addition to hydrogen, reformate (onboard reforming or fuel processing) remains an important option for fuel cell vehicles and other applications today despite the issues with CO_2 and other emissions, and expense as low cost reserves diminish. The better efficiency of fuel cells and reduced emissions can buy time to make a global transition to other renewable sources of electricity for hydrogen production.

Future Directions and Challenges for Fuel Cells

Fuel cell applications today are at a field trial level, or early commercialization stage, moving into volume commercialization. One study shows the estimated growth rate of hydrogen fuel cell cars in the world market to be from 1 in 10,000 cars in 2004, to 1 in 100 in 2010, to 1 in 4 cars in 2020.[3] Despite the significant advances made in fuel cell technology, there still remain a number of challenges for fuel cells going forward which include: improved fuel cell performance and root causes of performance effects; low cost materials with high volume process capability; improved reliability and lifetime for real operation; better predictive models and accelerated test methods; further simplification and improvement of the fuel cell stack and system; reduced impact of fuel cells on life cycle (cradle to grave); and fuel infrastructure and storage.

Summary

There are significant global environmental issues with existing energy paths today. Global emission and fuel regulations, global fuel and power structure, and cost are driving new technologies and non-conventional approaches. Fuel cells will play a significant role in the strategy to effect positive global change. Smaller fuel cell plants ideally suited for distributed power are cost competitive with other competitive technologies, and larger conventional centrally located power plants. Battery and hybrid systems (non-fuel cell) do not meet overall requirements for transportation with respect to energy density and range. However, fuel cell technology alone has reached a level that meets or exceeds targets identified by auto-makers (hybrids may offer further advantages). Power density, energy density, dynamic and operational response, cost potential, and operation on multiple fuels has been clearly demonstrated even for the most technically challenging transportation applications. However, significant challenges and opportunities still remain for improvement in fuel cell technology. These include improving the fuel cell power life cycle (cradle to grave) and improving hydrogen fuel storage (container/tank size and storage density) for an overall fuel cell environmental solution. Further significant improvements in fuel cell system (including tank/fuel) power density and energy density are expected (> 1,000 W/kg and > 1,000 Whr/kg). Zero emission strategies for hydrogen manufacture from fossil fuels and renewable sources are in progress. Fuel cells and a hydrogen infra-structure are key to a long-term solution to global energy issues. ■

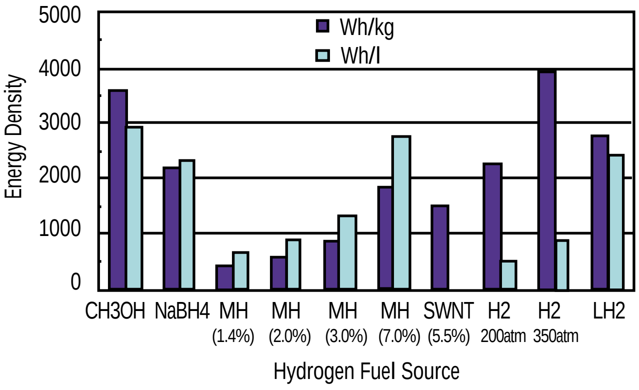


Fig. 8. Energy density for storage of different hydrogen fuel sources (MH = metal hydride; LH_2 = liquid hydrogen; SWNT = single walled nanotube).

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