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Fuel cell commercialization issues for light-duty vehicle applications

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Abstract

The major challenges facing fuel cells in light-duty vehicle applications relate to the high cost of the fuel cell stack components (membrane, electro-catalyst and bipolar plate) which dictate that new manufacturing processes and materials must be developed. Initially, the best fuel for a mass market light-duty vehicle will probably not be the best fuel for the fuel cell (hydrogen); refueling infrastructure and energy density concerns may demand the use of an on-board fuel processor for petroleum-based fuels since this will increase customer acceptance. The use of fuel processors does, however, reduce the fuel cell system's efficiency. Moreover, if such fuels are used then the emissions benefit associated with fuel cells may come with a significant penalty in terms of added complexity, weight, size and cost. However, ultimately, fuel cells powered by hydrogen do promise to be the most efficient and cleanest of automotive powertrains.

Keywords: Fuel cells; Commercialization; Light-duty vehicles

1. Introduction

This paper is intended to explain the resurgence of interest in fuel cells for automotive applications in recent years and to outline the significant challenges that lie ahead in developing fuel cells for commercialization. A key aspect to this issue involves the choice of fuel and the three leading fuel contenders (hydrogen, methanol and petroleum-based fuels) are each analyzed from a complete systems perspective with near-term and long-term issues emphasized.

2. What is a fuel cell?

Fuel cells create electricity directly from fuel, as shown in Fig. 1 [1–3]. Hydrogen or hydrogen-rich gas is fed through channels in a bipolar plate into the anode of the fuel cell. The electrode is coated with a catalyst that allows electrons to be stripped off, to produce hydrogen ions (protons), at relatively low temperatures (~85 °C). These electrons can energize a drive motor to turn the wheels of a vehicle and then return to the cathode and combine with the airstream, fed through channels in the other side of the bipolar plate, to produce oxygen anions. Meanwhile, in the case of the proton exchange membrane (PEM) fuel cell, the hydrated protons pass through a PEM electrolyte and link up with these oxygen anions to produce water, which is exhausted via channels in the bipolar plate on the air side.

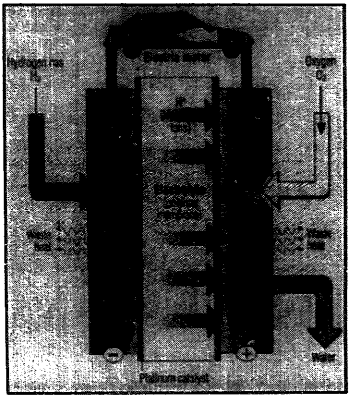

Fig. 1. Principle of fuel cell operation [1].

The net effect is identical with the combustion of hydrogen in air except that the transfer of electrons has occurred separately from the chemical union so that electricity is obtained directly. In theory, this process is extremely efficient; in practice, however, the fuel cell efficiency is lowered due to several polarization losses and there are three distinct operating loss regimes of the fuel cell stack, as shown in Fig. 2 [2]. Firstly, the slow reaction at the oxygen electrode creates the need for an equilibrium shift to boost the exchange current and this

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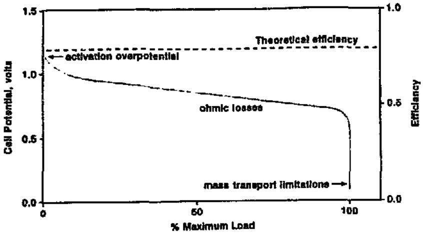


Fig. 2. Fuel cell stack efficiency vs. load curve [2].

shift, called the activation overpotential (or polarization), causes a logarithmic drop in efficiency even at very light current draw. Under typical power loads ohmic polarization losses, caused by the electrical resistance of the stack components (membrane, electrode, bipolar plate and connecting leads), produce an additional linear drop in efficiency. Ultimately, the limiting power output of the stack is dictated by the concentration polarization. In this regime, the necessary high inflow of reactants and removal of products, demanded by high-power operation, cannot be met because of hydrodynamic flow limitations in the stack; in the limit, all the fuel's chemical energy is converted directly into heat instead of electricity. Despite these losses, hydrogen-powered fuel cells have, according to Ballard Power Systems and Daimler–Benz AG, demonstrated 65% stack efficiencies and 45–50% system efficiencies during typical driving (the system efficiency curve differs from the stack efficiency curve for reasons explained later) [4].

When a fuel cell is used to propel a vehicle it shares several attributes with battery-powered vehicles (low or even zero-tailpipe emissions, low noise, modularity and reasonable shape flexibility, perhaps similar manufacturing processes, need for electric drivetrain, etc.) while its fuel/air intake and exhaust pipes, the available waste heat for cabin warming, and the relatively high energy density/low cost/rapid refueling of fuel storage systems evoke comparison with conventional vehicles and may help to overcome the main obstacles to batteries.

Despite being the ideal fuel for a fuel cell the difficulties associated with hydrogen (see later) make petroleum-based fuels worthy of consideration. In such cases an on-board fuel processor is required to create a hydrogen-rich gas with very low CO content since the latter is an effective poison to the fuel cell platinum electro-catalyst (that is required to ensure the reaction occurs rapidly at close-to-ambient temperatures).

3. Why are the automakers interested in fuel cells?

There are at least three reasons why automakers worldwide are increasingly becoming interested in fuel cells: energy efficiency, environmental cleanliness and international competition.

The energy efficiency of a fuel cell can be defined as the fuel cell system net power output integrated over the Environment Protection Agency (EPA) City/Highway Cycle divided by the lower heating value of the fuel consumed over the same cycle. Unfortunately, there is currently inconsistency as to how to standardize net power; a clear example is the amount of catalyst loading that should be used when comparing fuel cells from different manufacturers.

Contrary to popular belief, it should be noted that today's mass production internal-combustion engine (ICE) is not limited by Carnot Cycle efficiency limitations, which can, for example, be theoretically over 70% for compression ratios above 20:1; rather, its constraints such as fuel quality, materials properties, friction and emissions regulations that place practical limits on engine efficiency and vehicle fuel economy. Similarly, as explained previously, the efficiency of a practical fuel cell is also far below its fundamental limit and may even be less efficient than an advanced direct injected compression-ignition ICE when they both consume the same liquid hydrocarbon fuel. The relative efficiency advantage of the fuel cell system, over conventional spark-ignition engines, shown in Fig. 3, is seen particularly under light-load conditions which is significant because most driving occurs under these conditions.

The potentially greater efficiency of the fuel cell does not, by itself, produce a benefit to Society since one must also determine the efficiency with which the fuel can be made. ICE can, and do, burn primary fuels (fuels that occur naturally on Earth or can be refined relatively easily) whereas the PEM fuel cell must use secondary, or manufactured, fuels such as hydrogen or methanol (in the case of the direct methanol oxidation fuel cell). Since hydrogen can be made renewably from a vast array of sources — many fuel cell advocates claim that the fuel cell is fuel flexible — however, this is not an advantage because the same fuel can also be burnt in an ICE. Moreover, from an automotive standpoint, the need to either store or generate hydrogen on-board indicates that the fuel cell is not fuel flexible! Despite this, Governments of the developed world appear to see a long-term energy efficiency improvement in using fuel cells; if, for example, renewable hydrogen can replace gasoline in the long-term then the greater vehicle efficiency of the fuel cell may be an advantage

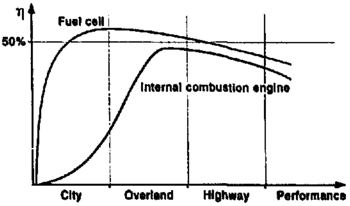


Fig. 3. Energy conversion efficiencies [4].

over burning the same fuel in an engine. However, even this may not be definite because comparably high efficiencies may even be attainable using hydrogen in a lean-burn spark ignition engine, particularly if it is hybridized, a strategy proposed by Smith at the Lawrence Livermore National Laboratory [5].

The second potential advantage comes from the fact that the conversion process in the fuel cell occurs at a much lower temperature than in a heat engine and so, unlike burning hydrogen in an engine, there is no NO_x formation and, since there is no lubricating oil in the fuel cell, there are also no hydrocarbon and CO emissions — in short, it can be used to propel a zero-emission vehicle (ZEV). However, as Daimler–Benz has shown, it is possible to burn hydrogen so leanly in an ICE that the exhaust NO_x concentration is immeasurable and, therefore, an oxidation catalyst can efficiently convert the lubricating oil emissions into water and CO_2 [6]. Skeptics suggest that increased water emissions, produced by hydrogen's combustion, pose a global warming threat but this ignores the fact that water is consumed in the production of hydrogen from steam reforming of natural gas so that there is no extra water produced than if the natural gas was burnt directly; if hydrogen is made from electrolysis of water then there is no net water produced at all. Clearly, as with battery-powered electric vehicles, the remote production of hydrogen does produce emissions and CO_2 and should, on a technical and environmental basis, be included when discussing relative improvements in air quality and global warming.

Even if methanol, or petroleum-based fuels, are processed on-board to produce hydrogen, the emissions may still be well below ultralow-emission level (ULEV) standards, and may even qualify as ZEV when fully-accounted, because the processing conditions are vastly different from stoichiometric mixture combustion; the potential for emissions reduction is, therefore, considerable, as shown clearly in Fig. 4 [7]. Although the fuel cell creates no criteria emissions itself, the trace CO allowed by the PEM fuel cell (a few ppm) will exhaust into the atmosphere untreated and if it is burnt then some NO_x emissions can be generated unless a catalyst is used in, or after, the burner. In contrast with today's ICE that uses exhaust after treatment, on-board fuel processing can be likened to a form of intake pre-treatment. Unfortunately, the fuel processor's lower emissions capability, relative to a catalytic converter, does come with a significant penalty in terms of cost, weight, size, response time (both start-up and transient) and complexity. (Even though ICE technology has become much more complex over the last twenty years this change has been made in an evolutionary manner and this is significant!)

The third reason for interest in fuel cells is the competition from abroad, which has recently spurred the USA to treat fuel cells as a critical technology. Since fuel cells have many applications (efficient stationary power generation is another obvious example) it is quite conceivable that even if fuel cells can never be made cost-competitive with the ICE for automotive uses (where the customer tends to regard initial cost as more important than lifetime cost savings) they may still become competitive with US $500–US $1000/kW gas turbine generators for electricity generation; in short, the automotive industry, by bringing its mass production expertise to bear on this issue, may open up many other applications for the PEM fuel cell.

As a result of the significant potential that fuel cells possess in addressing long-term regulatory drivers most automakers currently have PEM fuel cell programs in place. This type of fuel cell is considered the most attractive for light-duty vehicular application because all the other types, at present, have major drawbacks that may be difficult to overcome, e.g. the need for CO_2-free fuel and air, compactness, rapid start-up/shut-down, etc. Within the USA, each of the Big 3 (GM, Ford and Chrysler) has a separate cost-sharing program with the Department of Energy (DOE). General Motors Corporation has been working with Ballard on a methanol–steam reforming fuel cell program for several years while Ford Motor Company and Chrysler Corporation have just started their respective on-board hydrogen fuel cell programs. They differ in that Ford has chosen to work with several US fuel cell manufacturers, with the aim of selecting the most prom-

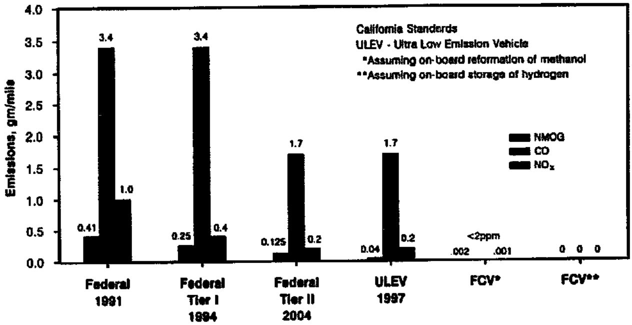


Fig. 4. Fuel cell vehicle emissions levels [7]; NOMG: non-methane organic gases.

ising fuel cells at a later date, while Chrysler has decided to work with Allied Signal, an established automotive supplier with expertise in materials R&D and systems integration. In summary, all major North American fuel cell developers are currently involved with an automotive program and each US automaker has taken a different approach. Moreover, the recently formed Partnership for a New Generation of Vehicles (PNGV), between the Big 3 and the US Government has set a goal of trying to produce an up-to-80 mpg mid-size sedan without sacrificing cost, safety, utility, emissions, etc., for early in the next century and it is clear that this aggressive goal has greatly helped to increase the visibility of fuel cells within the automotive industry.

Worldwide, Daimler–Benz has attracted much attention because of its fuel cell advocacy and has invested a significant amount in a collaboration with Ballard. Daimler–Benz has stated that Ballard's hydrogen fuel cell is the most efficient propulsion system it has ever tested and appears committed to developing a prototype before the end of this century [8,9]. Currently, there is a surging of interest within Europe which may lead to a EUCAR-funded fuel cell project involving several European automakers. Little is known about the Japanese automakers' programs except that Toyota Motor Corporation is attempting to develop stack components in-house and may demonstrate a methanol–steam reforming PEM fuel cell minivan in 1997 [10], while smaller Japanese automakers are testing out complete fuel cell systems from Ballard. A backdrop to this interest is the Japanese Government's WE-NET (World Energy NETwork) Project which has recently given a big boost to hydrogen and fuel cell technologies.

4. What are the key R&D challenges facing the PEM fuel cell stack?

The biggest challenge facing fuel cells is cost reduction. In order to be competitive with an ICE, PNGV has set technical and cost targets, shown in Fig. 5. For example, the fuel cell system (excluding fuel processor or hydrogen storage system) must cost about US $30/kW. If one considers a breakdown of the cost for each major component then the material cost for each of the three major parts of the fuel cell stack (membrane, electro-catalyst and bipolar plate) need to be around US $5/kW. Each of these components will be discussed briefly below.

Fuel cell system = stack + ancillaries required to operate stack, but not fuel processor / fuel storage

Fuel Cell System Goals

1) **Fuel cell system EPA Combined City / Highway Drive Cycle Efficiency (based on LHV): 55%**
2) **Power density: 400 W/L**
3) **Specific power: 400 W/kg**
4) **Cost: $30 /kW (continuous)**
5) **Start time (time to full power): 30 seconds**
6) **Operation: 5,000 hours and 100,000 miles**

Fig. 5. Fuel cell system PNGV goals.

An ideal membrane would have low cost, high ionic conductivity and poor electrical conductivity independent of water content, low permeability to reactant gases, high water transport, electrochemical stability towards redox environments, wide operating temperature range and high mechanical strength. Membrane costs could fall ten times if the volume increases a hundred-fold but since membranes are already manufactured in large quantities for the chlor-alkali industry (equivalent to about 10 000 fuel cell vehicles per year) the potential for cost reduction, through mass production, is probably not sufficient to drive the cost of today's best membranes down to ICE-competitive levels [11–13]. Novel materials and manufacturing processes are, therefore, being developed under the PNGV banner. For example, membranes optimized for automotive use can be less durable than those used in the chlor-alkali industry and should be designed for hydrogen transport, rather than sodium. It may be possible to achieve the necessary properties by using cheaper polymers, containing some hydrogen atoms instead of the more expensive fluorine [14]; more radically, it may be necessary to develop non-polymer-based membranes. Together with mass production these developments could drive the cost down toward automotive requirements.

Regarding the electro-catalyst, it should be remembered that platinum costs around US $400/oz (~US $15/g) and since the PNGV cost requirement for this component is around US $5/kW it implies that the platinum loadings should be around 0.3 g/kW. If 0.5 W/cm^2 cell performance is considered state-of-the-art then this requires platinum loadings of about 0.15 mg/cm^2 per cell. Unfortunately, there is little chance of completely new catalyst materials being viable, since the required properties are well known and restrictive, but improvements in understanding the morphology and developing new processing techniques can yield higher utilization and less expensive manufacture [15,16]. For example, recent single cell experiments at Los Alamos National Laboratory and Texas A&M University have reduced the platinum electro-catalyst loadings a hundred-fold to levels close to those used in a catalytic converter and, therefore, within the cost target [17]. However, it is unclear whether such low loadings are sufficiently durable to resist power decay due to CO poisoning in complete fuel cell systems. As the platinum loadings have been decreased, the original method of platinum deposition onto a polymer film has given way to the much more effective method of carbon-supporting and blending with Teflon [15]. Further research aimed at reducing the platinum content, either by increasing its utilization above the current 20% level or by creating cheaper palladium alloys, must be undertaken. Catalysts must also be developed that are more tolerant to CO (and perhaps CO_2) poisoning so that cost, weight and volume can be taken out of the fuel processing system and powertrain reliability can be increased. Finally, from a long-term research viewpoint, there is clearly a need to improve our fundamental understanding of the molecular processes occurring at the three-

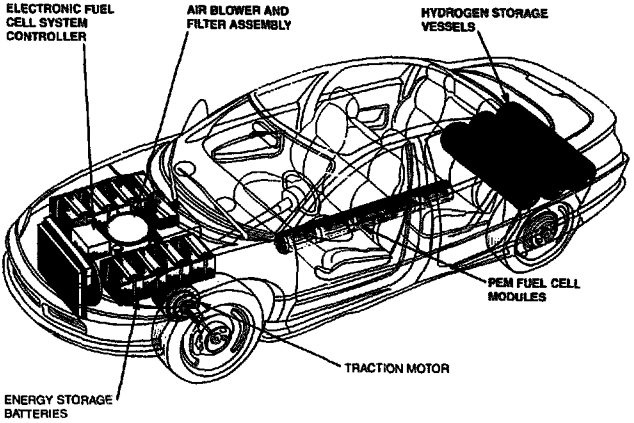


Fig. 6. Chrysler's concept fuel cell vehicle.

phase interface within the cell, since this will help improve the electro-catalyst component of the fuel cell stack [18].

The third component, the bipolar plate, may be the part of the stack that needs the most cost reduction in mass production [13]. This component needs to have low thermal mass and gas impermeability, and high electrical conductivity, corrosion resistance and mechanical strength. Meeting these objectives currently dictate that graphite be chosen as the bipolar plate material (metals typically cannot withstand the mildly corrosive acidic/redox environment and quickly develop an oxide layer that significantly lowers their electrical conductivity). Machining the graphite to create the flow channels for hydrogen, air and water (cooling) adds cost and is not viable for mass production. Several companies, e.g. Ballard, are, therefore, trying to develop metallic bipolar plates consisting of a cheap base metal and a thin protective coating [19]. This type of approach, or the development of highly conducting polymers may yield the solution to making the bipolar plate cheap and light; with the use of plastic parts creep may be a potential problem. Even without materials improvement, however, there is still scope for bipolar plate refinement. For example, flow field design is critical to the performance since it influences the power distribution across the membrane surface and can lead to the inadequate utilization of the electro-catalyst, at best, and hot spot formation with potential for leakage paths, at worst. As a consequence of this understanding of the bipolar plate's action, flow-field modeling has already yielded insights that have led to significant advances in stack power density.

Aside from cost, two other key PNGV targets for the fuel cell system are its power density and specific power. These goals correspond, respectively, to around 1 kW/l and 1 kW/kg for the fuel cell stack itself. It should be possible to meet these objectives within the ten-year timeframe of PNGV because tremendous progress has been made in recent years in several related areas (thinner and fewer bipolar plates, smaller humidification sections, improved membranes, etc.) [19]. These advances are made even more impressive if one recognizes the relatively small level of funding that fuel cells have received. Moreover, it should be noted, that packaging is critically important for light-duty vehicle applications and that, for equivalent power densities, the fuel cell stack appears to have an advantage over an ICE since it is modular and can probably be configured into a relatively wide array of shapes to take advantage of space on-board the vehicle. As Fig. 6 shows, Chrysler has decided to place the fuel cell stack down the tunnel of the car since this space would not otherwise be used. However, there are some constraints on the size and shape of the fuel cell stack. For example, a stack with a large active area requires relatively little manifolding and may reduce cost and complexity but it tends to produce a lower voltage and this reduces the efficiency of the electric drive; it may be possible for clever designs to overcome this apparent trade-off.

5. What are the key R&D challenges for the rest of the PEM fuel cell system?

As with an ICE, the concept of how power is produced is simple; however, a close look at a working ICE reveals how much more complex the system must become if it to be practical for vehicular use. The fuel cell stack cannot perform any useful function without the ancillaries, shown in Fig. 7 [20]. These provide humidification, cooling, and fuel and oxidant (air) supply. There is much interest in developing higher temperature PEM fuel cells, so that the product water can be removed as vapor, since this could lower the work

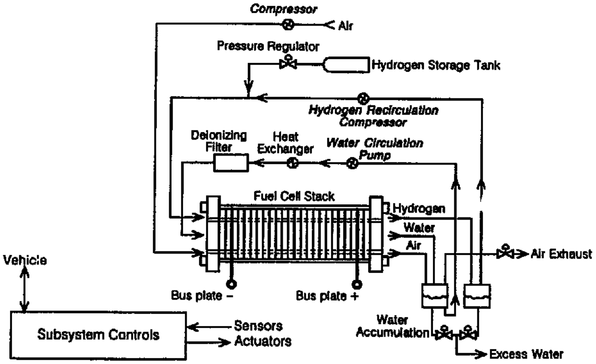


Fig. 7. Fuel cell system diagram [20].

required to expel it and, thus, generate higher voltages at high power densities. Moreover, the higher temperature would make the catalyst more tolerant to CO. However, operation of the fuel cell above 100 °C causes existing membranes to dry out and become non-conducting.

Among the ancillaries, it should be noted that the major power drain is the air sub-system. This is because the oxygen electrode kinetics are inherently slow, due to the formation of several poly-anion intermediates; in order to reduce this activation overpotential the partial pressure of oxygen needs to be increased, either by oxygen enrichment or by air compression.

Air compressors exact high power consumption (typically 10–15% of the fuel cell stack output) [12,21]. This parasitic loss causes the fuel cell system's efficiency to drop drastically when the fuel cell is operating at low power (below 10%-rated load, as shown in Fig. 3) even though the stack efficiency, itself, increases under these conditions, as shown in Fig. 2. Moreover, under conditions of high air compression the stack power output increases but not enough to compensate for the compression power requirements so that net power cannot be indefinitely increased. Development of a low-cost, highly efficient air compressor may actually do more to help system efficiency than further improvement of the membrane electrode assembly (MEA). For example, hot compressed exhaust gases may be able to offset some of the energy requirements for air compression, and hydrogen storage, either in compressed or liquid form, or fuel processor waste heat may also be usefully integrated.

Oxygen enrichment, an alternative to air compression, has the advantage in that the concentration of nitrogen diluent is lower and the potential for reducing the cost, weight and volume of the fuel cell stack appears attractive. However, the power requirements needed to create a pressure drop across the enrichment membrane, to push the oxygen through, appear to be excessive at present, as are the size and cost of the membrane [12]. In response to the problems caused by air compression or oxygen enrichment several research groups, e.g. Texas A&M University, are looking into operating the fuel cell stack at ambient pressure; even though this simplifies the system considerably it may create problems for expelling the product water and currently reduces the power density too much. Most of the other sub-systems do not represent a large efficiency or powerdrain but more work must be done in developing sensors for fuel cell applications and to optimize the fuel cell system's design for compactness and low cost and in customizing it for automotive use. For example, the need to operate reliably at sub-zero ambient temperatures means that the humidifying de-ionized water may have to be drained from the fuel cell system at key-off, or shutdown, while the coolant (which does not come into contact with the inside of the fuel cell) may need to contain antifreeze.

6. What constraints does the vehicle place on the fuel cell?

Apart from the obvious cost, weight and packaging targets, the automobile also places performance constraints on any technology. Even if fuel cells can be developed, that can produce useful power at −40 °C, the slow start-up of a fuel processor will probably demand that the vehicle be a hybrid that contains an energy storage component, such as a battery, flywheel or ultracapacitor. Hybridization may help to improve the vehicle's fuel economy because it enables regenerative braking and, perhaps, a reduction in the vehicle's weight (provided that batteries with a significantly higher specific power than the fuel cell system and with more specific energy than today's lead/acid battery can be developed so that the weight of an extra controller can be more than offset). Moreover, the battery can reduce the time that the fuel cell system spends below 10%-rated load, which is where the driven car spends much of its time. It also offers the possibility of the fuel cell system being completely turned off during idling and decelerating without compromising take-off performance; even though this benefit will be less for a fuel cell than for a heat engine it could still help fuel economy, as demonstrated in idle-off diesel engine vehicles produced by Volkswagen AG. Finally, hybridization could eliminate the need to consume hydrogen in order to keep the fuel cell in a state of user-readiness in very cold weather because the battery may be able to provide propulsion for the first few minutes of driving while the fuel cell warms up.

The highly variable dynamic range, typified by the urban drive mode, required for automotive application places great demands on the performance of any energy conversion device and it should be remembered that the conventional ICE's efficiency is considered low precisely because of this same dynamic range. For example, a typical combined powertrain (gasoline spark ignition engine and automatic transmission) efficiency over the City Cycle might be approximately 15% whereas over the Highway Cycle it might be 20–25% [22]. In both the EPA City/Highway Cycle and in real-life driving the start-up time can be a significant fraction of a journey's length and this procedure considerably lowers the efficiency of an ICE [23]. Since the PEM fuel cell operates optimally between 80 and 85 °C some efficiency will be sacrificed during warm-up but it is probably not as significant as for an ICE. At shut-down, hydrogen that is still present on the catalyst sites may either permeate across the membrane and be vented or, if a load is placed across the cell, continue to react. These effects will probably not be very significant but in either case fuel economy is likely to be reduced because energy is consumed without the vehicle moving.

Finally, and perhaps most importantly, the vehicle also puts major constraints on the choice of fuel. Three fuel choices will be discussed below: hydrogen, methanol and petroleum-based fuels. These cover the extreme cases of hydrogen, the best choice for the fuel cell, and gasoline, the best choice from an infrastructure point-of-view; methanol, by contrast, is considered a compromise between these two choices.

7. What are the key issues concerning the use of hydrogen?

Hydrogen is the ideal fuel for a PEM fuel cell and is intriguing because if it is made from the electrolysis of water and if the electricity is made from renewable resources, such as wind or sunlight, then the hydrogen production is also renewable by virtue of the water cycle. Currently, however, the cheapest method of making hydrogen is from steam reforming of natural gas so that the environmental and energy efficiency benefits of hydrogen are muted [24]. However, at some point in the future, as non-renewable fossil fuels either run out or are deemed environmentally unacceptable, and as renewable technologies, e.g. wind turbines, solar cells, etc., improve, the cost of renewable hydrogen should cross-over the cost of fossil fuels. The time taken for this will also depend on when, or if, agreement on external costs occurs.

A question that is frequently asked is 'Why not use the electricity directly instead of enduring the inefficiency of electrolyzers (for hydrogen generation) and fuel cells (for end-use application)?' [25]. The two main reasons are, firstly, that the energy density, specific energy and cost/kWh of batteries limit their usefulness today, and perhaps always, for mobile applications and, secondly, if energy is to be exported or transmitted over long distances then a carrier such as hydrogen may make economic and environmental sense. If batteries can be developed that meet the long-term US Advanced Battery Consortium (US ABC) goals then fuel cells may not be necessary but many doubt if this is possible.

There are, however, three principal concerns regarding the use of hydrogen in automobiles. Hydrogen safety, for example, is a controversial issue. Images of the Hindenburg and word association with hydrogen bombs continually reinforce the image that hydrogen is unsafe. The reality is that people are afraid of the unknown and hydrogen is rarely seen or used in public — nearly all the hydrogen produced in the world each year is consumed by industry, particularly the Petroleum Industry. Natural gas and gasoline, on the other hand, are commonly used by the public which has come to accept the danger because it routinely sees the benefits in using these fuels. Organizations that do have experience in using hydrogen (Daimler–Benz, BMW AG, Mazda Motor Corporation, NASA, etc.), and safety studies, that have been performed by several research laboratories, have come to the conclusion that, like any fuel, under certain conditions hydrogen can be more dangerous than gasoline whereas in other situations it may be safer [26,27]. The negative perception will have to be overcome, however, if hydrogen vehicles are to enter the marketplace and this will require vehicle demonstrations and continuous education, particularly of young, unprejudiced people. However, it is also clear that engineering and designing safe methods of storing hydrogen on-board a vehicle must be given critical importance and cannot be compromised. For example, there is still a need to develop odorants for hydrogen that will not poison the fuel cell since it is likely that customer acceptance may be hindered otherwise.

A second important non-vehicular issue associated with any fuel, and especially hydrogen, is refueling infrastructure. It is often said that hydrogen can piggyback off the natural gas infrastructure but reliance on this pathway may be ineffective given the slow pace with which a natural gas automotive infrastructure is emerging [28]; a hydrogen infrastructure will be significantly more of a challenge because of the lack of customer acceptance and also because there will probably be extra costs associated with several factors, such as the capitalization of the fueling station (a reformer is necessary in addition to the compressor), the vehicle storage tanks (because hydrogen has a lower energy density) and with the fuel itself [1,29]. Moreover, there are still some issues that need to be addressed concerning the compatibility of hydrogen with natural gas pipelines. Introduction via centrally-refueled fleets is frequently mentioned as the likeliest scenario for commercializing hydrogen-pow-

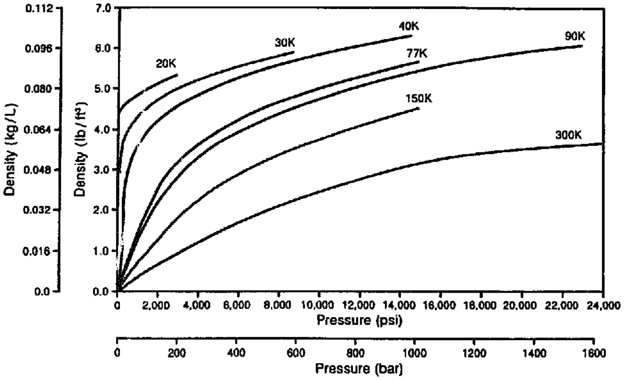


Fig. 8. Energy density of compressed hydrogen [30].

ered vehicles [28]. Although this is useful for demonstrating safety and technology it neglects the fact that fleet vehicle sales alone will not drive the cost of the hydrogen storage tanks and fuel cells down to gasoline tank and ICE mass production cost levels because there is a discontinuity in sales volume between fleet sales and mass market penetration. However, significant markets can exist for centrally fueled fleet vehicles (taxis, police cars, buses, delivery vans, etc.) and it should not be assumed that only liquid hydrocarbon fuels can be used for all vehicles.

One proposed method of overcoming the infrastructure issue is to use regenerative fuel cells that can act in electrolysis mode during charging at night, for example, and as a fuel cell during driving; the by-product of electrolysis, oxygen, could even be stored on-board and used as a power boost during accelerations while regenerative braking is also feasible. However, the extremely low full fuel cycle efficiency (< 10% or about half today's gasoline spark ignition (SI) engine full fuel cycle efficiency), the inability to generate more than 100 mile (~ 160 km) range from household charging overnight, the need for a battery during start-up on a cold day anyway, and the potential dangers associated with storing both oxygen and hydrogen on-board and of generating hydrogen inside household garages seem to make this approach impractical.

Another transitional possibility is to use petroleum-based fuels as the feedstock for making hydrogen (see later). Although this might not be the best solution from a full fuel cycle or vehicle efficiency standpoint it does offer the possibility of mass market penetration with all the economic and environmental benefits which can then result.

Apart from safety and infrastructure concerns, the third main issue in using hydrogen as an automotive fuel is its relatively low energy density. If the goal is only to develop a ZEV with superior range to a battery-powered vehicle then compressed hydrogen storage may be acceptable but if the goal is the replacement of today's mid-size sedan then a vehicle range of about 380 miles (~ 610 km) may be required and no form of hydrogen storage, with the possible exception of liquid hydrogen, currently meets this goal in a practical form.

The shape of the pressure/density curve, in Fig. 8, means that increasing the pressure indefinitely, even if it was economical, does not allow compressed hydrogen to match gasoline in energy density [30]. For example, about 12 lb (5–6 kg) of hydrogen is needed to propel an 80 mpg vehicle 380 miles (~ 610 km), and compressed hydrogen, even at 5000 psi (~ 340 bar), requires 8–9 ft^3 (60–70 gallons or 220–250 l) which is more than three times the volume of today's gasoline tank [31,32]. Moreover, studies at Chrysler seem to indicate that a 10 ft^3 (~ 280 l) packaging envelope may be necessary to cater for a tank holding 5 ft^3 (~ 140 l) of hydrogen because the high pressure carbon fiber tanks require thick walls and are non-conformable. For this reason, it is misleading to compare volumes of compressed hydrogen (or natural gas) with those of other fuels, including liquid hydrogen. Fig. 9, for example, shows that at 300 bar (~ 4350 psi) hydrogen's energy density is only three times better than sodium–sulfur batteries and if the fuel cell's efficiency and non-conformability of tanks are also considered then the packaging problem for a given range may not be much better than for the battery-powered electric vehicle although the weight should be less. As with batteries, another concern will be the fuel storage cost since Chrysler's experience with CNG-powered vehicles show that a fuel tank cost penalty of around US $2000 can be incurred (approximately half of the premium associated with natural gas vehicles) even though the vehicle's range is significantly compromised; however, the USCAR (US Council for Automotive Research — another Big 3/US Government collaboration) has recently set up a Natural Gas Vehicle Consortium and one of its objectives is to reduce the cost of natural gas storage tanks

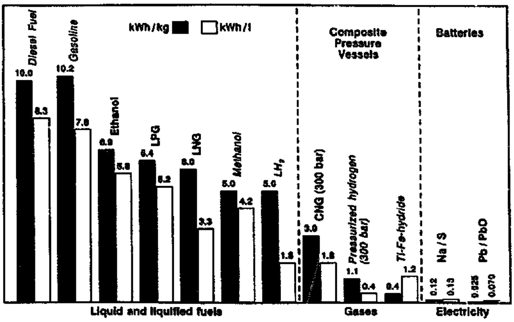


Fig. 9. Specific energies of fuel storage systems [31].

Hydrogen Storage Goals

1) Energy density (including tank): 2 kWh/L
2) Specific energy (including tank): 3 kWh/kg
3) Cost of tank: $2/kWh

Fuel Processor Goals

(Fuel processor system excludes fuel storage)

1) Fuel processor system EPA Combined City/Highway Drive Cycle Efficiency* (based on LHV): 80%
2) Power density: 500 W/L
3) Specific power: 1 kW/kg
4) Cost: $10/kW
5) Start time (time to full power): 1 minute
6) Transient response: 10 seconds
7) Emissions: Below Tier II level
8) Operation: 5,000 hours and 100,000 miles

* Efficiency is defined as ratio of
fuel processor-PEM fuel cell system drive cycle efficiency : H_2-PEM fuel cell system drive cycle efficiency

Fig. 10. Fuel processor/H_2 storage PNGV goals.

by 50% in 1998 through innovative materials and/or manufacturing. Hydrogen, by virtue (?) of having an energy density approximately four times lower than natural gas for the same pressure, will require a larger storage volume, or a higher pressure, even though the vehicle might be up to three times more efficient. It, therefore, appears likely that a compressed hydrogen-fuel cell propulsion system offering comparable range will cost significantly more than today's US $2500–US $3000 gasoline-ICE powertrain. If the PNGV goals, outlined in Fig. 10, are met then the cost of a hydrogen storage system capable of propelling an up to 80 mpg (~3 l/100 km) vehicle 380 miles (~610 km) will be US $300 while the volume (80 l or ~21 gallons) and weight (50–60 kg, or ~110–130 lb) would be roughly comparable with today's gasoline tank. Even if these stretch targets are reached it will still force the fuel storage system to incur a large cost penalty compared with today's gasoline tank and this cost differential will need to be offset elsewhere on the vehicle.

Another method of storing hydrogen is to absorb it into a metal but the only metal hydrides that currently seem able to liberate their absorbed hydrogen using waste heat from the PEM fuel cell are the low-temperature hydrides, which store around 2 wt.% hydrogen (for the whole metal hydride system which should include heat exchangers and containment) [33]. Because 5–6 kg (12 lb) of hydrogen may be needed to provide the required range it means that the hydride must weigh more than 250 kg (~550 lb); this weight not only reduces fuel economy but will likely cost more than the total ICE powertrain used today.

Hydrogen can also be adsorbed onto activated carbons so that storage occurs in both gaseous and adsorbed phases. The present generation of carbon adsorbents, admittedly optimized for natural gas rather than for hydrogen, only outperform compressed hydrogen at relatively low pressures; under these conditions most of the gas is stored in the adsorbed phase, but the energy density is far too low to be practical. On the other hand, at pressures above 3000 psi (207 bar) the carbon tends to block more space than it adsorbs and straightforward compressed hydrogen is more energy dense [34]. Cryogenic treatment significantly improves the energy density but it does this for the compressed gas anyway and it adds complexity from a customer standpoint. Finally, the use of carbons and metals to store hydrogen introduce several control issues such as poisoning and heat liberation during refueling.

Because of these limitations in hydrogen storage great hope is being placed in quantum leap technologies such as buckyballs, microspheres and conformable compressed gas tanks; there are even proposals to use hydrogen carriers such as cyclohexane and ammonia [33].

In reality, however, liquid hydrogen may be the only 'effective' method of storing hydrogen with a relatively high energy density and specific energy. However, it also suffers from several problems such as cryogenic handling, a long refueling time, venting and, most importantly, energy-intense production; typically 50% of the liquid hydrogen's stored energy might be needed in the transition from the natural gas wellhead to the vehicle's powertrain consumption (in terms of reforming, liquefaction and transfer and storage losses) [35]; this is unacceptable if the aim is to reduce global warming and improve the efficiency with which we use natural resources. Of this 50%, approximately 30% is due to liquefaction energy and is driven largely by the Second Law of

Thermodynamics. Eventually, if hydrogen can be made renewably at a cost effective price then the inefficiency of production will be decoupled from CO_2 liberation and resource depletion, and the favorable economics of overland transport of liquid hydrogen should make it commercially viable compared with other forms of hydrogen. BMW believes in the long-term potential of liquid hydrogen and has helped to advance the development of well-insulated cryogenic tanks and rapid refueling technologies [36].

In summary, hydrogen faces daunting commercialization issues near-term and only in a long-term scenario (renewable hydrogen economy) can a strong case be made for it. Liquid hydrogen is probably the only means of storage that might be viable unless the public begins to accept marked reductions in vehicle range. Unlike every other method of hydrogen storage, liquid hydrogen requires engineering improvements, e.g. superior insulation, rather than fundamental research breakthroughs.

8. What are the key issues concerning the use of methanol?

Natural gas is the feedstock from which both methanol and hydrogen are made most economically but steam reforming natural gas on-board a vehicle requires high temperatures that demand long start-up times and a significant reduction in the vehicle's fuel economy given the light-duty cycle of the vast majority of passenger vehicles, e.g., most trips are shorter than 30 min [23]. For utility applications, however, where start-up times are not so important then development of natural gas steam reforming fuel cells hold much promise.

Natural gas may not be regarded as a convenient fuel to store and transport and so it may be considered justifiable to convert it into an ambient-temperature liquid fuel, such as methanol, which is relatively energy-dense and provides a conceptually simple infrastructure transition. Having already been processed external to the vehicle, methanol does not require such high steam reforming temperatures and in a sense, methanol can be considered as liquid hydrogen (strictly speaking, liquid hydrogen plus CO). This relative ease of reforming allows methanol to provide a higher fuel cell system's efficiency than with other conventional fuels [37,38]; moreover, in contrast with gasoline, methanol's homogeneous composition and relatively high purity could simplify fuel processing considerably.

Methanol, like hydrogen, is also capable of delivering power directly in a PEM fuel cell without the need for reforming and this direct methanol oxidation fuel cell clearly simplifies hardware and response characteristics; the military is actively involved in developing these systems as replacements for batteries in several types of applications. However, the power density and efficiency are several times lower than for hydrogen (or methanol reforming) systems because a large fraction of the input methanol crosses over the membrane and is oxidized at the cathode without producing useful power [39]. Finding membranes that can prevent this cross-over or developing cathode catalysts that do not oxidize the methanol are major research objectives. Another problem is that, due to the high activation overpotential at the methanol anode, the platinum catalyst loadings must be several mg/cm^2 and this amounts to several hundred dollars per kW, which is prohibitively expensive for automotive applications.

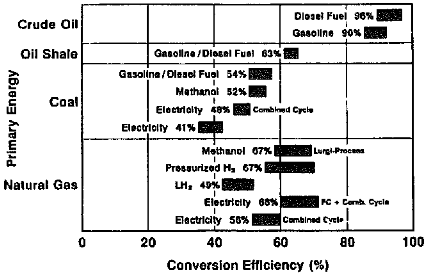


Fig. 11. Fuel production efficiencies [40].

As a fuel, there are several major challenges to widespread methanol usage. In the near-term, the efficiency of methanol's production from natural gas is so low (~67%), as shown in Fig. 11, that the benefits in terms of global warming and conservation of natural fuel resources are lost relative to using natural gas or diesel in an advanced heat engine [40,41]. Moreover, since the cheapest sources of methanol are from abroad (remote natural gas), the diversity of overseas sources will provide some improvement in energy security but it may not reduce the trade deficit very much.

Setting up a methanol infrastructure may be a non-trivial issue since it is possible that existing oil pipelines cannot accept methanol without modification to the linings and valves due to methanol's corrosiveness (which creates an additional toxicity concern in terms of customer handling). The need for very high-purity methanol, demanded by the PEM fuel cell, may also be difficult to deliver using existing pipelines [41]; these possible requirements for higher purification and overland transport will increase fuel cost. Another pragmatic issue concerns the long-term investment that petroleum companies have in the existing infrastructure and the need to allow time to recoup their investment costs; they also control the prime-site refueling stations.

If any fuel is to replace gasoline then it will probably need to show long-term promise since it may be impractical to change infrastructures more than once. Advocates of methanol point out the long-term potential of making methanol from biomass (methanol is sometimes called wood alcohol because it can be made from the pyrolysis of wood) so that the full fuel cycle efficiency and CO_2 production can be completely decoupled. (That methanol is renewable and has an advantage over gasoline needs some clarification. Biodiesel can be made from a variety of renewable oils and fats and is biodegradable, non-toxic and practically free of sulfur

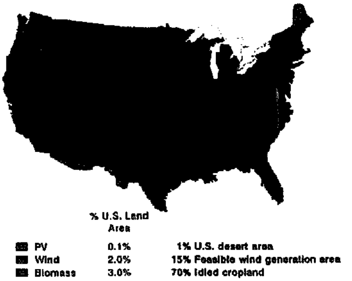


Fig. 12. Renewable energy land requirements [42].

and aromatics; gasoline or diesel can even technically be made from syngas (CO/H_2) using the Fisher–Tropsch Process; this is uneconomically practiced in South Africa (as insurance against sanctions). Syngas can be made from several sources including landfill waste (natural gas steam reforming) and biomass (methanol steam reforming).

However, there are many issues that have yet to be satisfactorily addressed regarding the renewable methanol scenario. Biomass is, in effect, very low efficiency solar collection so that the land requirements to supply the US vehicle fleet's energy needs must be at least twenty times larger than if man-made photovoltaic collectors are used to create solar hydrogen via electrolysis, as shown in Fig. 12 and as the efficiency of solar cells increases so will this land area differential [42]. If crop rotation is required in order to ensure that the land stays fertile the land requirements may need to be increased even more and may clash with those required for growing food and fodder and, perhaps, construction materials and feedstock for the paper industry [43,44]. Moreover, there will be some competition to use the biomass to make valuable chemicals and plastics rather than energy. Such large-scale biomass production may also create havoc for local ecosystems, and may need large amounts of irrigation water, and pesticides and fertilizers that may add to the CO_2 inventory in the atmosphere — for example, it takes more energy to make ethanol from grain than is returned as ethanol fuel. Finally, this scenario makes the vehicle fleet's energy requirements susceptible to fluctuations in biomass production. Renewable hydrogen production, by contrast, is multi-source and may include solar electricity (southwest USA), wind-power (Dakotas), biomass (the Midwest), municipal solid wastes (MSW), hydroelectric, etc. Failure in one mode can be made up by excess production elsewhere and there is, clearly, immense potential for energy exports. Moreover, development of cost-effective solar and wind power can lead to the development of high-tech industries and further export potential.

MSW can, perhaps, solve many of the problems associated with biomass although there is the concern that conversion of dormant landfill waste into fuel will liberate CO_2 in the same way that dormant fossil fuels do. It seems reasonable that if the ultimate goal is to eliminate CO_2 emissions completely then the surest way to achieve this might be to eliminate its production rather than to try and cancel out production with consumption.

It is likely that the passenger vehicle transportation fuel of the future will need to have a nationwide infrastructure since consumers will always want to refuel wherever they choose to travel. Moreover, a strong case for an international infrastructure may be made since many consumers travel between countries (at the moment this is particularly true in Europe) and if vehicle manufacturers are forced to make vehicles for different markets that operate on different fuels this will tend to increase complexity and vehicle cost.

In conclusion, methanol may become a significant regional or supplemental fuel, particularly if municipal solid wastes or croplands currently subsidized by taxpayers to not grow crops are used. It is difficult to imagine methanol replacing petroleum as the ubiquitous transportation fuel in the near-term whereas, in the long-term, it faces a strong challenge from liquid hydrogen; the latter can be made renewably from a wider array of sources, and also be stored compactly on-board a vehicle and may provide a much higher vehicle efficiency, zero emission and a much less complex fuel cell powertrain with improved start-up and transient response characteristics.

9. What are the key issues concerning the use of petroleum-based fuels?

There is a need to look at the PEM fuel cell's fuel choice from a different perspective because hydrogen is long-term and methanol does not provide enough near- or long-term benefits.

If fuel cells are to be commercialized then they will need to be mass-produced and this implies that there will have to be an extensive fuel infrastructure in place at that time. Moreover, petroleum-based fuels have several attractive features such as high specific energy and energy density (packaging and weight are key issues in a fuel cell vehicle), low fuel cost (probably the only area where the 80 mpg (~ 3 l/100 km) Next Generation Vehicle may save the customer money) and proven customer acceptance of the fuel's safety. Since the transportation of any fuel from production site to service station is around 99% the well-to-vehicle efficiency remains around 85–90% for gasoline and diesel and just over 60% for methanol [41]; this difference may make the gasoline, or diesel, full fuel cycle efficiency higher than for methanol or liquid hydrogen and comparable with compressed hydrogen, when all are used with a PEM fuel cell. Petroleum refining typically uses natural gas as input fuel so that nearly all the carbon contained in the petroleum ends up as gasoline or diesel. Therefore, to a good approximation, a comparison of CO_2 production with parallel production efficiency even though petroleum's C:H ratio is higher than for natural gas;

FUEL FEATURE AFFECTED BY CHOICE	Direct hydrogen	Steam reforming of methanol	Partial oxidation of petroleum-based fuels (e.g. gasoline, diesel)
On-board efficiency	1	2	3
On-board emissions	1	2=	2=
Cradle-to-grave efficiency and emissions	1=	3	1=
Fuel cell system complexity	1	2=	2=
Fuel cell system response	1	3	2
Vehicle cost	1	2=	2=
Fuel cost	3	2	1
Safety (perceived)	3	2	1
Infrastructure	3	2	1
Vehicle range	3	2	1

1 (best) → 3 (worst) – All used in conjunction with fuel cell and compared with each other

Fig. 13. Fuels' comparison for fuel cell vehicles.

vehicle efficiencies, however, will not parallel CO_2 production.

In summary, an analysis of energy density/specific energy, fuel cost and fuel storage tank cost, emissions and efficiency (both vehicular and full fuel cycle), fuel safety (perceived or real) and infrastructure will affect the choice of optimum fuel, as shown in Fig. 13 — the ratings shown are partly subjective and the criteria do not have equal weight, but the conclusion is that, in choosing the best fuel for a fuel cell vehicle, automakers may well decide to adapt the fuel cell around the vehicle rather than defining the best fuel for a fuel cell (hydrogen) and trying to persuade the infrastructure to provide, and the public to use, this fuel.

The previous statements lead to a rationale for, at least, considering petroleum-based fuels in fuel cell vehicles, but can these fuels be used with PEM fuel cells? Petroleum-based fuels can be converted into hydrogen on-board the vehicle using a partial oxidation (POX) process that has already been extensively practiced by the Petroleum Industry for use in upgrading their feedstocks [38]. This process is essentially fuel-rich combustion and is probably limited to around 80% efficiency for liquid hydrocarbons (based on the ratio of diesel POX fuel processor/PEM fuel cell system drive cycle efficiency: hydrogen/PEM fuel cell system's drive cycle efficiency) [38,45]. This efficiency may be lower than the steam reforming of methanol but, as mentioned before, the difference is unlikely to offset the much higher efficiency with which reformulated diesel is produced compared with methanol. It should be noted that POX reactors and steam reformers are means of generating hydrogen and that a fuel processor also includes CO clean-up since this is necessary for a PEM fuel cell.

PNGV goals for the fuel processor are shown in Fig. 10 but it should be noted that, compared with methanol steam reformers, the POX reactor may be smaller and simpler, although the water gas shifter will probably be larger since the CO concentration is higher and the hydrogen partial pressure is much lower; the combined volume of the two types of fuel processor/fuel tank may, therefore, be comparable since the diesel/gasoline storage is approximately half the size of a methanol tank. The POX system should produce a faster start-up and transient response and may have multi-fuel capability, even for the catalyzed version [46]. These advantages accrue because air is used instead of steam and because there is a relaxation on the catalyst requirements. For both types of fuel processor, however, the $10/kW cost goal (reformer plus CO-clean up) will be a significant challenge.

The major technical challenge for any fuel processor, and the POX version in particular, will be to maintain the borderline 80% efficiency of the whole unit while reducing its size from that used in oil refineries where heat integration is relatively easy to use on-board a vehicle where space is critical; this is made even more difficult by the fact that the POX reactor's hydrogen product gas is diluted with unreacted nitrogen from the air, and this creates either an equivalent Nernst potential reduction or an energy drain in compressing the fuel stream. Moreover, the fuel that is used will have to be desulfurized to prevent catalyst poisoning and in order to reduce the size of the low-temperature water shift catalyst bed.

Advances in materials are needed to improve the POX fuel processor technology. Examples include better reforming catalysts (higher thermal stability, activity and selectivity) and start-up combustion catalysts that are less expensive and operate at lower temperatures to lower NO_x [47]. The separation membranes, considered for oxygen enrichment, may be critical to the viability of fuel processors because it is desirable for the hydrogen to be separated from the remaining reformate gases (mainly CO, CO_2, N_2) without using bulky, high thermal mass shift reactors since the latter increase the start-up and transient response times. The relatively large difference in size between hydrogen and these gases does help in the separation but the twin needs of ensuring that there is no loss in hydrogen transmission (wasted fuel) and of complete separation (less poisoning) probably make the task far more difficult than for oxygen separation from nitrogen. Hydrogen separation typically occurs via a different mechanism than oxygen separation since it relies on an adsorption — diffusion — desorption pathway and the palladium catalyst loadings, despite being in very thin layers, need to have large active areas, and are presently far too expensive for automotive applications.

One consequence of the POX approach is clear, as shown in Figs. 14 and 15: the need to make the fuel cell viable for automotive applications requires the addition of many ancillary sub-systems and fuel processing and these have the effect of reducing the overall efficiency down to a level which may still be superior to today's spark ignition engine but might be inferior to that of an advanced direct injection compression ignition engine operating on a similar fuel. This will be even more so if the efficiency of electric motors and controllers cannot be made to be as high as those of conventional mechanical (manual) drivetrains that are commonly used in Europe. However, it seems likely that they will be more efficient than automatic transmissions, which is the type that

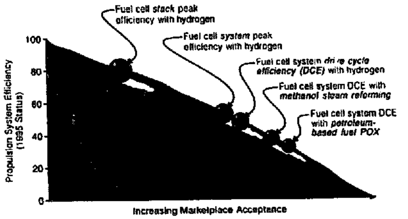
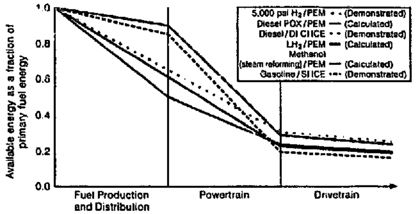


Fig. 14. Powertrain efficiencies (1995 status).



N. B. Figures shown are approximate values over the combined city/highway drive cycle and are meant to indicate only that there is *not* a significant difference between advanced heat engines and fuel cells when a well-to-wheels analysis is performed

Fig. 15. Full fuel cycle analysis for various fuels and powertrains.

is most widely used in the USA, although lock-up torque converters may change this.

One might then ask why not use diesel fuel in an advanced direct-injected compression-ignition engine and obtain comparable vehicle and full fuel cycle efficiency with reduced engineering and economic challenge? One reason is that the tailpipe emissions from the fuel cell vehicle should be much lower because the fuel-rich combustion associated with POX ensures that, with proper control, NO_x emissions should be negligible and soot formation may also be eliminated [48]; however, it should be noted that start-up and transient emissions are still largely unknown. Another perceived benefit is that, unlike batteries or methanol–steam reforming/ hydrogen fuel cells, any hydrocarbons or CO in the ambient air might also be treated in the POX reactor to make water and CO_2 as has been demonstrated, on occasion, in conventional ICEs. Moreover, unlike the ICE there will be no lubricating oil emissions and there may even be no evaporative emissions because today's volatile cold-start butane additives should not be necessary. These factors might allow the POX/PEM fuel cell to meet foreseeable emissions regulations, even perhaps ZEV on a fully-accounted basis; confidence in this prediction comes largely from the Georgetown University methanol steam-reforming PEM fuel cell bus which has demonstrated emission levels which are orders of magnitude below ULEV.

Another reason for pursuing the POX approach, in parallel with the advanced diesel engine, is that oil import reduction may be comparable, even if the efficiency turns out to be lower than that of an advanced diesel engine. The reason for this apparent contradiction is that the POX reactor should be far more fuel flexible than a compression ignition engine. Provided that the fuel is desulfurized it should be possible to use a wide variety of oil fractions ranging from lighter fractions than gasoline to heavier fractions than diesel, since the slight difference in H:C ratio can probably be accounted for by on-board computer sensing that can regulate different amounts of water for the shifting process. If, on the other hand, a natural gas automotive infrastructure develops more rapidly than expected the use of an on-board CNG POX reactor might even be viable since CNG should simplify the fuel processing system, is three to four times denser than hydrogen and has greater customer acceptance. CNG could be converted into hydrogen at the refueling station by using the steam methane reformation process (SMR).

Another benefit of the POX reactor is that the fuel cell's pathway helps to enable does lead to a long-term scenario that is considered desirable, as shown in Fig. 16. Clearly, such a strategy will require the support of governments, industry and public that share a long-term vision. For example, if fuel cells can be commercialized because of their use of quasi-conventional fuels then there is the potential to replace the POX reactor with hydrogen storagetanks if the latter have improved to an acceptable level (or with liquid hydrogen) and once hydrogen education has had time to work. In other words, the POX reactor could be transferred to the 'gasoline' station in a transition stage while in the even longer-term, renewable hydrogen should become economical and this will certainly make liquid hydrogen worthy of consideration.

Such a transition allows time for the oil industry to prepare for future changes and allows a continuous pathway of both increasing vehicle and full fuel cycle efficiency and decreasing vehicle and full fuel cycle emissions. This is especially true for the vehicle efficiency where one might expect greater room for improvement with the relatively immature fuel cell than with a heat engine, e.g. a 20–40% improvement in the power density is expected in the next few years [13]. Vehicle efficiency is highly significant when the long-term fuel is made renewably because the end-use efficiency and emissions are critical to the full fuel cycle efficiency and emissions.

10. How will fuel cells be commercialized for automotive applications?

Before ending this paper it is necessary to deal with an Automotive Industry business perspective. It should be noted that, for example, in each of the light-duty vehicle fuel cell projects currently taking place worldwide, the fuel cell development is being funded primarily by governments and is usually being performed by PEM fuel cell developers and not by the automakers. This procedure is typical of any emerging automotive technology where in-house knowledge and experience cannot compete with that of specialist manufacturers.

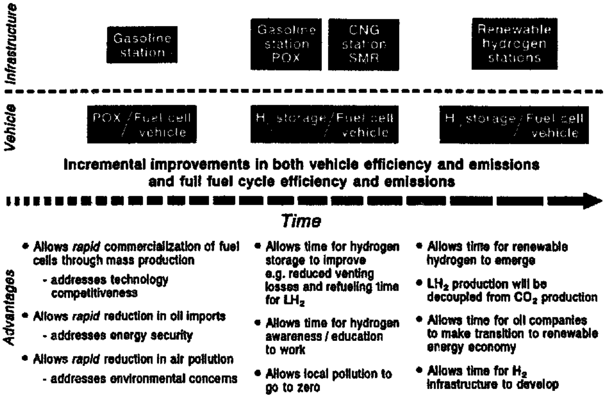


Fig. 16. One potential pathway to a renewable future.

When, or if, fuel cells becomes commercially viable it can be expected that the fuel cell developers may license the proprietary technology to companies with mass production expertise, such as the automakers or automotive suppliers.

If one compares today's automobile with that of a car twenty years ago it is obvious that many new technologies have been successfully commercialized. For example, many of the standard features in today's cars (fuel injection, air conditioning, catalytic converters, anti-lock brakes, etc.) were once considered premium options. Their entry into the market place has traditionally come through the luxury end of the vehicle spectrum. If the technology proves commercially attractive then this encourages efforts to increase production and this, in turn, brings the costs down and attracts new buyers. This gradual shift from small volume, high variable cost to large volume, low variable cost often takes place with a transfer of production from the original small scale inventors to either the vehicle manufacturers or to the Tier I auto suppliers. Clearly, introduction of fuel cells will be much more difficult than those components mentioned above because it will also require the simultaneous introduction of a new fuel, unless it runs on gasoline. The refueling infrastructure may limit customer appeal of the new powertrain and discourage automakers from large scale production.

A common misconception is that automakers are opposed to introducing new powertrains because they pose a threat to the automaker's core engine technology and key value-added expertise. In today's environment, the core expertise of vehicle manufacturers lie mainly in areas other than powertrain development and manufacture; styling, vehicle system design and integration, manufacturing, marketing, distribution and financing are, in fact, core strengths and may make it very difficult for small-scale electric car-builders to pose a large threat [49]. In the automotive sector, there is a global movement away from vertical integration and to rely more and more on the 'extended enterprise', resident in the supplier community to such an extent that a large fraction, often the majority, of most vehicles is made by suppliers. The Aerospace Industry takes this trend to extremes and even outsources engines and airframes while maintaining expertise in the areas of system integration and development of strategically sensitive components.

In the particular case of hybrid vehicles, the vehicle's system controller may be a core differentiator between different manufacturer's products in that it helps to create the powertrain 'feel'. Different vehicle manufacturers may then purchase the same components or sub-systems and differentiate their products in the market place by their in-house control strategy. Automakers may also decide to manufacture electric powertrains but, given that motors tend to be relatively simple devices compared with ICE, this is probably a less critical core competency.

11. Summary

Operation of the fuel cell on a petroleum-based fuel may be a necessary condition for rapid and early commercialization but it is not sufficient. Improvements still needs to occur in the fuel cell stack, ancillaries and fuel processor, and much greater attention to mass production manufacturability needs to be given before it can be considered suitable for light-duty vehicle applications.

In order to make the fuel cell practical for vehicular applications it requires the addition of many sub-systems and these have the effect of making the fuel cell less practical from a cost-efficiency, weight, volume and complexity standpoint! Moreover, the fuel cell must be coupled to an electric drive and, because of drivability concerns, will need to be hybridized. This means that fuel cell commercialization is also dependent on improvements occurring in other immature technologies.

The need to use conventional fuels/fuel processors and the significant improvements that can be expected in competing energy conversion device technologies appear to make it unlikely that a fuel cell will replace the heat engine on efficiency grounds alone, in the near-term, although the fuel cell does hold out the promise of higher long-term efficiency and lower near-and long-term emissions. However, the fuel cell's emissions benefit when a fossil fuel is stored on-board exacts a high price since the fuel processing (intake pre-treatment) strategy adds significantly to the complexity, weight, size and cost of the system. The perceived advantage (efficiency) and disadvantage (power density) of fuel cell stacks may conceivably be reversed in the near future!

Ultimately, as hydrogen from renewable sources becomes economically competitive with fossil fuels then a strong case can be made for using liquid hydrogen storage, since it is the only form of hydrogen storage that does not require a fundamental breakthrough and the time-frame involved should allow refinements to cryogenic storage, that obviate concerns regarding dormancy and handling. The inefficiency of its production from renewable energy can also be decoupled from CO_2 liberation and its position as the most easily transported method of hydrogen storage should continue to make it the cheapest form of hydrogen delivered to the consumer.

The next few years will, perhaps, be key to the future for PEM fuel cells since the recent involvement by automakers gives it the best chance it has ever had to become viable.

References

[1] R.H. Williams, *Technol. Rev.*, (Apr.) (1994) 20–30.

[2] L.J.M.J. Blomen and M.N. Mugerwa, *Fuel Cell Systems*, Plenum, New York, 1993.

[3] A.J. Appleby and F.R. Foulkes, *Fuel Cell Handbook*, Van Nostrand Reinhold, New York, 1993.

[4] T. Klaiber (Daimler–Benz), personal communication, Nov. 1994.

[5] J.R. Smith, The hydrogen hybrid option, in K.L. Stricklett (ed.), *Proc. Advanced Components for Electric and Hybrid Electric Vehicles Workshop, 27–28 Oct. 1993*, National Institute of Standards and Technology (NIST), *Special Publication No. 860.*

[6] H. Buchner, Hydrogen technology for mobile applications, *Proc. 4th US Annual Hydrogen Meet., Alexandria, VA, USA, Mar. 1993.*

[7] H.E. Helms and P.J. Haley, Development of a PEM fuel cell system for vehicular application, *SAE 921541*, US Society of Automotive Engineers, Warrendale, PA, USA, 1992.

[8] Daimler–Benz presents Europe's first Fuel Cell Vehicle, a Milestone on the Road to Ecological Mobility", *Reuter Press Release*, 13 Apr. 1994.

[9] Daimler–Benz May Present Fuel Cell Vehicle in 1996, *Reuters Business Rep.*, (26 July) (1995).

[10] K. Dircks (Ballard), personal communication, May 1995.

[11] M. Deluchi, Hydrogen fuel-cell vehicles, *Res. Rep. UCD-ITS-RR-92-14*, Institute of Transportation Studies, University of California, Davis, CA, USA.

[12] Technology development goals for automotive fuel cell power systems, *Final Rep. Contract No. 228 22S 402*, Directed Technologies, Inc., Prepared for Argonne National Laboratories, Aug. 1994.

[13] *Fuel Cell Technology for Transportation Applications: Status and Prospects*, Arthur D. Little, Inc., Rep. for US Department of Energy, 1995

[14] A.E. Steck, Membrane materials in fuel cells, *Proc. New Materials for Fuel Cell Symp., Montreal, Que., Canada, July 1995*, pp. 74–94.

[15] H. Wendt, New electrocatalysts for fuel cells, *Proc. New Materials for Fuel Cell Symp., Montreal, Que., Canada, July 1995*, pp. 532–543.

[16] G. Hards, T. Ralph, D. Thompsett and M. Gascoyne, Catalyst and electrode development for the solid polymer fuel cell, *Electrochem 94 Conf., Edinburgh, UK, Sept. 1994.*

[17] S.S. Penner, Center for Energy and Combustion Research, University of California, San Diego, CA, USA, submitted to US Department of Energy, Office of Program Analysis, Germantown, MD, USA.

[18] P. Eisenberger (ed.), *Basic Research Needs for Vehicles of the Future Workshop*, Princeton Materials Institute, Princetowen University, NJ, 1995

[19] K.B. Prater, *J. Power Sources, 61* (1996) 105.

[20] D.-G. Oei, Direct hydrogen-fueled proton-exchange membrane (PEM) fuel cell for transponation, *SAE TOPTEC*, Warrendale, PA, USA, Mar. 1995.

[21] D.H. Swan, B.E. Dickinson and M.P. Arikara, Proton-exchange membrane fuel cell characterization for electric vehicle applications, *SAE 940296*, Warrendal, PA, USA, 1994.

[22] L.J. Oswald, Tutorial on hybrid electric vehicles, *ESD's Environmental '95 Conf., Dearborn, MI, USA, Jan. 1995*, Society for Automotive Enegineers, Warrendale, PA, USA.

[23] R.Q. Riley, *Alternative Cars in the 21st Century: A New Personal Transportation Paradigm*, SAE Publications, Warrendale, PA, USA, 1994.

[24] J.E. Funk, Hydrogen production: a tutorial, *10th World Hydrogen Energy Conf., Cocoa Beach, FL, USA, June 1994.*

[25] C.A. Kukkonen and M. Shelef, Hydrogen as an alternative automotive fuel: 1993 update, *SAE 940766*, Warrendale, PA, USA, 1994.

[26] J.G. Hansel, G.W. Mattern and R.N. Miller, *Int. J. Hydrogen Energy, 18* (1993) 783–79.

[27] M.A. Deluchi, *Int. J. Hydrogen Energy, 14* (1989) 81–130.

[28] J.M. Ogden, J.W. Strohbehn and E. Dennis, *Hydrogen Energy System Studies*, Center for Energy and Environmental Studies, Princeton University.

[29] R.H. Williams, Fuel Cells, Their fuels, and the US automobile, *1st Annual World Car 2001 Conf., University of California, Riverside, CA, USA, June 1993.*

[30] I. Kuhn (Directed Technologies, Inc.), personal communication, Oct. 1994.

[31] T. Klaiber (Daimler–Benz), personal communication, Nov. 1994.

[32] Hydrogen for power applications, Task 2: Storage of Hydrogen in Solid, Liquid and Gaseous Forms, Florida Solar Energy Center, *Subcontract No. XK-7-07158, FSEC-CR-204-88*, June 1988.

[33] A.T-Raissi, Tutorial on hydrogen storage gaseous and solid forms, *10th World Hydrogen Energy Conf., Cocoa Beach, FL, USA, June 1994.*

[34] S. Hynek, W. Fuller, J. Bentley and J. McCullough, *Proc. 10th World Hydrogen Energy Conf., Cocoa Beach, FL, USA, June 1994*, pp. 985–1000.

[35] W. Peschka, *Int. J. Hydrogen Energy, 12* (1987) 753–764.

[36] Hydrogen — A versatile energy carrier, *BMW 1994 Engineering Conf, Munich, Germany.*

[37] R. Williams, personal communication, Princeton University, Jan. 1995, (original source: R. Katofsky, Arthur D. Little, Inc.).

[38] Y. Jamal and M.L. Wyszynski, *Int. J. Hydrogen Energy, 19* (1994) 557–572.

[39] C. Lamy and J.-M. Leger, New electrocatalytic materials for the direct methanol fuel cell: an opportunity for the development of electric vehicles, *Proc. New Materials for Fuel Cell Symp., Montreal, Que., Canada, July 1995*, pp. 296–309.

[40] T. Klaiber (Daimler–Benz), personal communication, Nov. 1994, (original source: Shell).

[41] R. Katofsky and J. Bentley, Energy supply infrastructure for fuel cell vehicles, *NESEA S/EV 94*, North East Sustainable Eenergy Association, Rhode Island Convention Center, Providence, RI, USA, Oct. 1994.

[42] J.M. Ogden, *Renewable Hydrogen Energy System Studies*, Center For Energy and Environmental Studies, Princeton University, USA, 1993.

[43] C. Flavin and N. Lensson, *Power Surge*, W.W. Norton and Co., Worldwide Institute Copyright, New York, 1994.

[44] R. Golob and E. Brus, *The Almanac of Renewable Energy*, Henry Holt and Co., World Information Systems Copyright, New York, 1994.

[45] R. Williams (Princeton University), personal communication, Jan. 1995, (original source: R. Katofsky, Arthur D. Little, Inc.).

[46] R. Kumar, S. Ahmed, M. Krumpelt and K.M. Myles, Reformers for the production of hydrogen from methanol and alternative fuels for fuel cell powered vehicles, Argonne National Laboratories, *Rep. No. ANL-92/31*, Argonne, IL, USA.

[47] J.C. Amphlett, R.F. Mann and B.A. Peppley, Materials used in fuel processing for PEM fuel-cell power systems, *Proc. New Materials for Fuel Cell Symp., Montreal, Que., Canada, July 1995*, pp. 249–267.

[48] D. Moard (Hydrogen Burner Technology), personal communication, Dec. 1994.

[49] Potential impact of electric vehicles on the automotive business system, *Int. Motor Business 2nd Quarter 1995*, Economist Intelligence Unit, London, UK.